13 PAGAN

13.1 Introduction

One of the most active volcanic islands in the Mariana Archipelago, Pagan is located at 18°07′ N, 145°48′ E, 52 km north of Alamagan and 65 km south of Agrihan. Two large stratovolcanoes, or tall, cone-shaped volcanoes with layered internal structure, formed this island, and a low-lying, narrow isthmus connects them (Fig. 13.1a). Pagan extends north to south for 17 km and is 7 km across at its widest point. With a land area of 47.75 km^2, Pagan is the fourth largest island of the Commonwealth of the Northern Mariana Islands (CNMI). The highest elevation on this island, at 570 m, is the peak of Mount Pagan, which dominates the northern part of this island (Fig. 13.1b). South Pagan has a maximum elevation of 548 m.

Volcanic activity on Pagan has been recorded fairly regularly since the 17th century, with all of the verified activity originating from Mount Pagan volcano (Siebert and Simkin 2002–). The largest known eruption occurred in 1981 and forced the evacuation of this island's residents. Lava flows from this eruption dominate the landscape of northern Pagan. More recently, Mount Pagan erupted in December 2006 and August 2010 and possibly in April 2009, and thermal emissions have been observed in subsequent years (Siebert and Simkin 2002–).

Figure 13.1a. Satellite image of Pagan, labeled to show Shomushon Village and Pagan Airstrip (© 2006 DigitalGlobe Inc. All rights reserved).

Figure 13.1b. Mount Pagan, as seen from the NOAA Ship *Hi'ialakai* in 2007. *NOAA photo*

13.1.1 History and Demographics

Evidence of historic occupation of Pagan by the Chamorro people was discovered by Georg Fritz, the first German administrator, when visiting this island in 1901 (Spennemann 2006). Fritz found basalt latte sets, sling stones and cultivated plants, all evidence of Chamorro culture. During the early 1900s, Pagan, populated at the time, was leased by the German government to the Pagan Gesellschaft for copra production. Copra production was the mainstay of the German economy in the Marshall Islands and in much of Micronesia; however, a series of typhoons in 1905 and 1907 resulted in a 50% reduction in production for several years (Spennemann 1999b).

After World War I, Pagan was awarded to Japan for administrative authority, as were the other islands of the Northern Mariana Islands. During World War II, more than 4000 Japanese troops and 1000 laborers were stationed on Pagan until their surrender to U.S. Army representatives in September 1945 (Rottman 2002). Following that war, a small U.S. Navy installation was established on Pagan. The main settlement on Pagan was a village called Shomushon on the northwestern coast of Pagan (Fig. 13.1a), but this village was destroyed by flooding and debris flows after the 1981 eruption (Trusdell et al. 2006). In 1981, the eruption of Mount Pagan volcano prompted the evacuation of this island's 53 residents (Siebert and Simkin 2002–). Since then, inhabitation on Pagan has been sporadic, with 6–10 persons observed during Mariana Archipelago Reef Assessment and Monitoring Program (MARAMP) cruises.

Part of the Northern Islands Municipality of the CNMI, Pagan is one of the islands where land could be designated for village and homesteading programs. The *Northern Islands Homestead Act of 2008*, which was signed into law by the Governor of the CNMI in January 2010, may increase the population in coming years. This legislation, CNMI Public Law 16-50, recognizes that residents of the "islands north of Saipan" have no formal homesteads, allows residents to have agricultural lots and facilities, encourages resettlement by former residents, and initiates and promotes economic development.

13.1.2 Geography

Two stratovolcanoes originally formed Pagan, and more recent volcanoes have developed within these large calderas (Siebert and Simkin 2002–). The northern caldera is 7 km wide and contains a low-lying crater within which 2 lakes have formed. Lagona Lake, also known as Laguna Sanhiyon, near the west coast and an interior lake near the western foot of Mount Pagan hold the only nonstream water present in the northern islands of the CNMI (for place-names and their locations, see Figure 13.2a in Section 13.2: "Survey Effort"). From this large caldera, Mount Pagan emerges. South Pagan has an elongated summit with 4 distinct craters (Siebert and Simkin 2002–).

Large calderas form the northern and southern sections of this island, and relatively few steep slopes are present on Pagan (Fig. 13.1.2a). The highest slopes on northern Pagan are found on the inner walls of the craters. The narrow isthmus that separates the two parts of this island is dominated by a narrow ridge with very steep slopes on either side. South Pagan has steep slopes around South Point. Although much of the coastline of Pagan is rocky, several beaches allow easy access to this island.

The geology of northern Pagan is characterized by lava flows and deposits from eruption events (Fig. 13.1.2b). The oldest rocks are lava flows from the Holocene Epoch (11,700 years to present) on the northwestern and eastern flanks of Mount Pagan that have not been capped by more recent deposits (Trusdell et al. 2006). South of the large northern caldera, Holocene tuff deposits are also found. West of the Mount Pagan summit, a large maar (or shallow crater resulting from an eruption caused by groundwater mixing with magma) contains deposits from pyroclastic flows varying in age from 50 to 600 years (Trusdell et al. 2006). On the northeastern and southern flanks of Mount Pagan, lava flows originating from an 1872–1873 eruption are present, although many of them have been topped by lava flows from the large eruption in 1981 (Trusdell et al. 2006).

The geology of the isthmus and southern Pagan has not been as extensively studied as the geology of northern Pagan. However, geologic investigations conducted in 1954 indicated that the isthmus and southern peninsula are characterized by geologic strata originating before the large calderas were created, while South Pagan volcano is dominated by lavas originating after the large calderas were created (Fosberg and Corwin 1958).

The eruption in 1981 included lava flows on the northeastern and northwestern flanks of the Mount Pagan volcano. Flows on the southwestern flank reached within 1 km of the village of Shomushon and covered half of Pagan Airstrip (Figs. 13.1.2b and 13.1a; Trusdell et al. 2006). This eruption resulted in extensive ash fall over Pagan and the neighboring island of Agrihan, ~ 65 km north of Pagan. Volcanic activity was recorded through the late 1980s and early 1990s, and more recently, eruptions with ash fall and plumes were observed in December 2006 and August 2010, a possible eruption with steam plumes was recorded in April 2009, and thermal emissions were detected in the subsequent years (Siebert and Simkin 2002–).

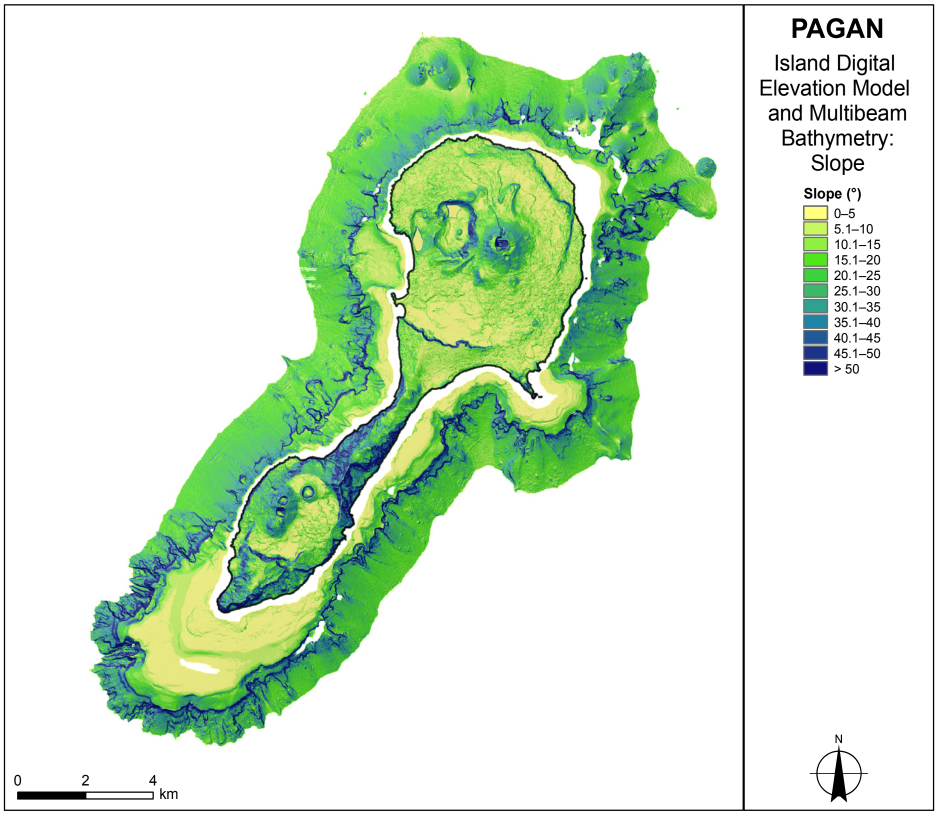


Figure 13.1.2a. Combined slope map using the digital elevation model and bathymetry data for Pagan (grid cell size: 10 m).

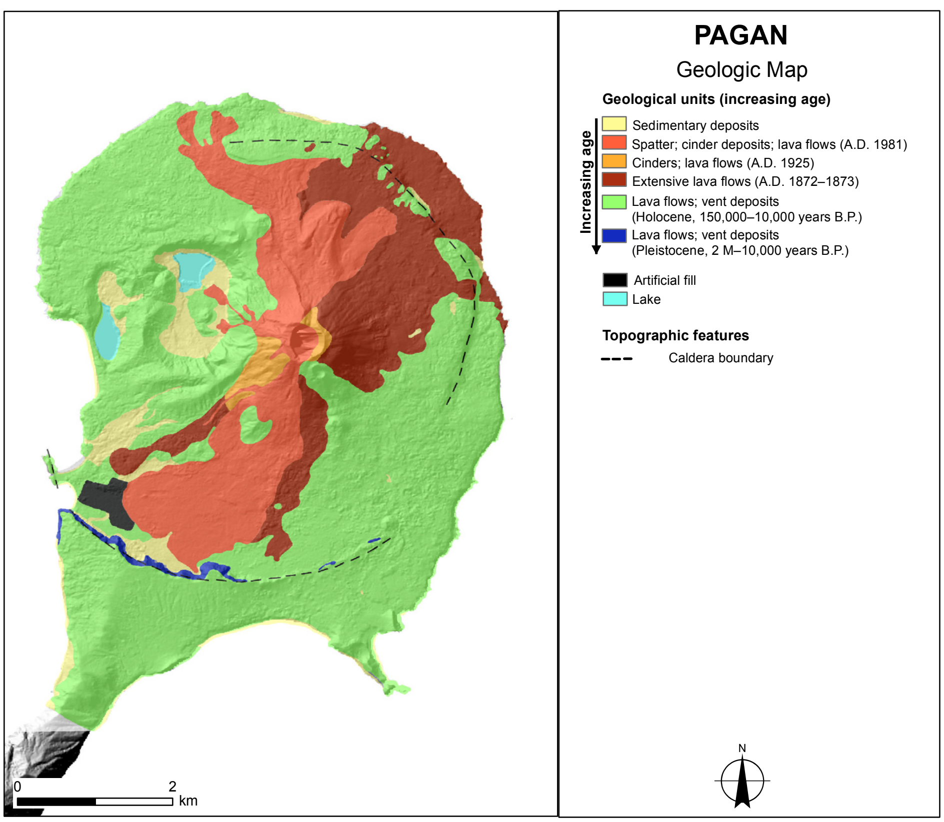


Figure 13.1.2b. Geologic map of Mount Pagan (adapted from Trusdell et al. 2006).

Except for areas covered by the most recent lava flows and volcanic deposits, the majority of Pagan is vegetated. Where recent volcanic material is vegetated, it supports pioneer vegetation, such as sword grass (*Miscanthus floridulus*) that is able to survive on a porous substrate. Around this island's 2 lakes, marshy areas and thickets of broad-leaved trees are present. Forest habitats on Pagan are fragmented and have suffered degradation from feral animals. Forests are present in valleys and ravines, on either side of the lava flows on the northern flanks of Mount Pagan, and on the western slopes of this island's isthmus (Cruz et al. 2000; Mueller-Dombois and Fosberg 1998). Small native patches remain, but forests primarily are composed of non-native species, including abundant *Casuarina equisetifolia*, an invasive tree (Cruz et al. 2000). Other introduced or non-native species on Pagan include the coconut palm (*Cocos nucifera*), tangan-tangan (*Leuceana leucocephala*), and physic nut (*Jatropha curcas*; Cruz et al. 2000).

Little information is available regarding the distribution of groundwater resources on Pagan. The 2 lakes in the northern caldera are filled with brackish water, and local groundwater supplies feed fumaroles (vent from which steam or hot gases escape) on Mount Pagan (Evans et al. 1987).

13.1.3 Environmental Issues on Pagan

One of the biggest environmental concerns on Pagan is the impact of feral animals on the native forests of this island (Cruz et al. 2000). Grazing by feral animals has removed natural vegetation and created a lack of a seedling understory, preventing future regeneration and resulting in dry soil and increased erosion.

The remaining, vulnerable patches of native forest on Pagan are important as habitat for native wildlife. Pagan supports a number of native birds, including the Micronesian starling (*Aplonis opaca*), Micronesian honeyeater (*Myzomela rubrata*), and a small population of the Micronesian megapode (*Megapodius laperouse*), a bird listed both as an endangered species Federally (U.S. Fish and Wildlife Service) and as a threatened or endangered species locally (Berger et al. 2005). The Mariana fruit bat (*Pteropus mariannus mariannus*), an endemic subspecies listed Federally as threatened (U.S. Fish and Wildlife Service) and locally as threatened or endangered (Berger et al. 2005), is present on this island with an estimated population of 1500 individuals in 2000 (Cruz et al. 2000).

Surveys conducted by the Division of Fish and Wildlife (DFW) of the CNMI Department of Lands and Natural Resources around planned homestead sites in 2000 indicated that no species of concern were located in the potential homestead areas and that northern Pagan was well suited to agriculture and ecotourism. Harvesting of natural resources from the coral reef ecosystems around Pagan would need to be managed to ensure sustainable use. In contrast to northern Pagan, southern Pagan supports a number of species of concern, and management of the feral animals in this area has been recommended by the CNMI DFW. Other potential environmental issues that may require management are erosion and sedimentation that could result from commercial ash mining in the future. The successful applicant likely would be required to develop harbor facilities and construct housing and associated infrastructure. Development of this new industry could change the economic and natural landscape of Pagan (Cruz et al. 2000).

13.2 Survey Effort

Extensive biological, physical, and chemical observations collected under MARAMP have documented the conditions and processes influencing coral reef ecosystems around the island of Pagan since 2003. The spatial reach and time frame of these survey efforts are discussed in this section. The disparate areas around this island often are exposed to different environmental conditions. To aid discussions of spatial patterns of ecological and oceanographic observations that appear throughout this chapter, 4 geographic regions around Pagan are delineated in Figure 13.2a; wave exposure and breaks in survey locations were considered when defining these geographic regions. This figure also displays the locations of the Rapid Ecological Assessment (REA) surveys, towed-diver surveys, and towed optical assessment device (TOAD) surveys conducted around Pagan. Potential reef habitat around this island is represented by a 100-fm contour shown in white on this map.

Benthic habitat mapping data were collected around Pagan using a combination of acoustic and optical survey methods. MARAMP benthic habitat mapping surveys conducted around Pagan and Agrihan with multibeam sonar covered a total area of 2511 km^2 in 2007. Optical validation and habitat characterization were completed using towed-diver and TOAD surveys that documented live coral cover, sand cover, and habitat complexity. The results of these efforts are discussed in Section 13.3: "Benthic Habitat Mapping and Characterization."

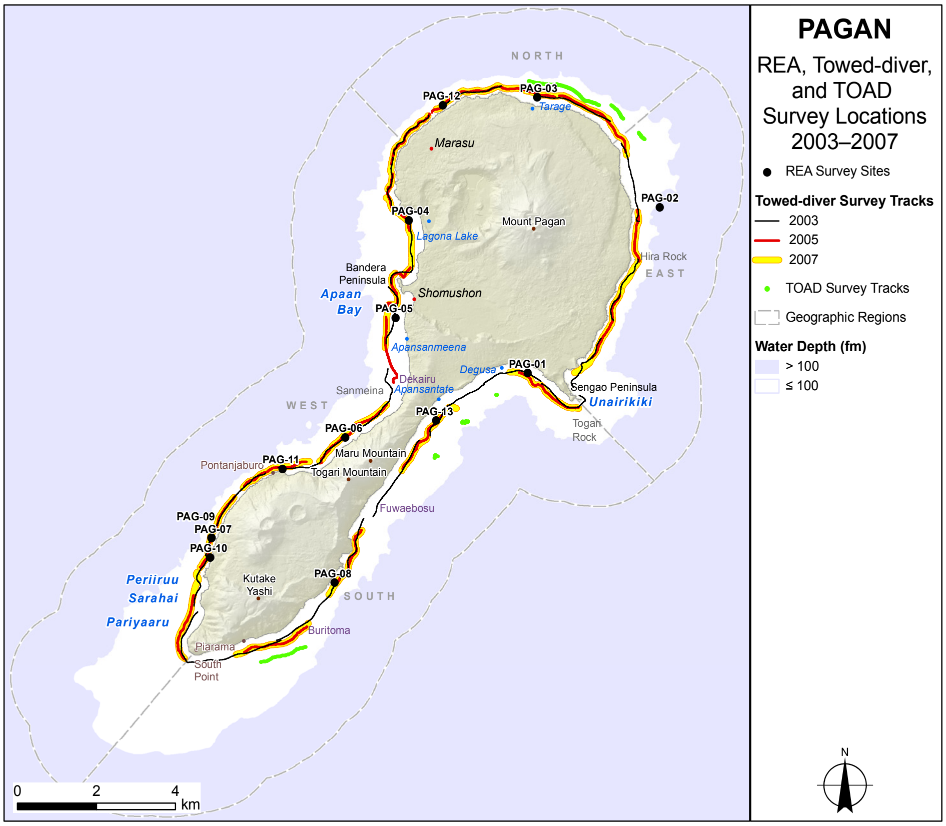


Figure 13.2a. Locations of the REA, towed-diver, and TOAD benthic surveys conducted around Pagan during MARAMP 2003, 2005, and 2007. To aid discussion of spatial patterns, this map delineates 4 geographic regions: north, east, south, and west.

Information on the condition, abundance, diversity, and distribution of biological communities around Pagan was collected using REA, towed-diver, and TOAD surveys. The results of these surveys are reported in Sections 13.5–13.8: “Corals and Coral Disease,” “Algae and Algal Disease,” “Benthic Macroinvertebrates,” and “Reef Fishes.” The numbers of surveys conducted during MARAMP 2003, 2005, and 2007 are presented in Table 13.2a, along with their mean depths and total areas and length.

Spatial and temporal observations of key oceanographic and water-quality parameters influencing reef conditions around Pagan were collected using (1) two types of moored instruments designed for long-term observations of high-frequency variability of temperature, (2) closely spaced conductivity, temperature, and depth (CTD) profiles of the vertical structure

Table 13.2a. Numbers, mean depths (m), total areas (ha), and total length (km) of REA, towed-diver, and TOAD surveys conducted around Pagan during MARAMP 2003, 2005, and 2007. REA survey information is provided for both fish and benthic surveys, the latter of which includes surveys of corals, algae, and macroinvertebrates.

Survey Type	Survey Detail	Year		
REA		**2003**	**2005**	**2007**
Fish	Number of Surveys	7	9	9
	Mean Depth (m)	11.5 (SD 1.7)	12.6 (SD 1.7)	12.6 (SD 1.7)
Benthic	Number of Surveys	10	9	9
	Mean Depth (m)	11.9 (SD 1.8)	12.6 (SD 1.7)	12.6 (SD 1.7)
Towed Diver		**2003**	**2005**	**2007**
	Number of Surveys	21	17	16
	Total Survey Area (ha)	38.7	30.9	33.6
	Mean Depth (m)	12.9 (SD 1.7)	15 (SD 1)	14.8 (SD 1.3)
TOAD		**2003**		
	Number of Surveys	7		
	Total Length (km)	5.48		

of water properties, and (3) discrete water samples for nutrient and chlorophyll-*a* analyses. CTD casts were conducted during MARAMP 2003, 2005, and 2007, and water sampling was performed during MARAMP 2005 and 2007. Results from some casts and water samples are not presented in this report because either the data were redundant or erroneous or no data were produced (see Chapter 2: "Methods and Operational Background," Section 2.3: "Oceanography and Water Quality"). A summary of deployed instruments and collection activities is provided in Table 13.2b. Results are discussed in Section: 13.4: "Oceanography and Water Quality."

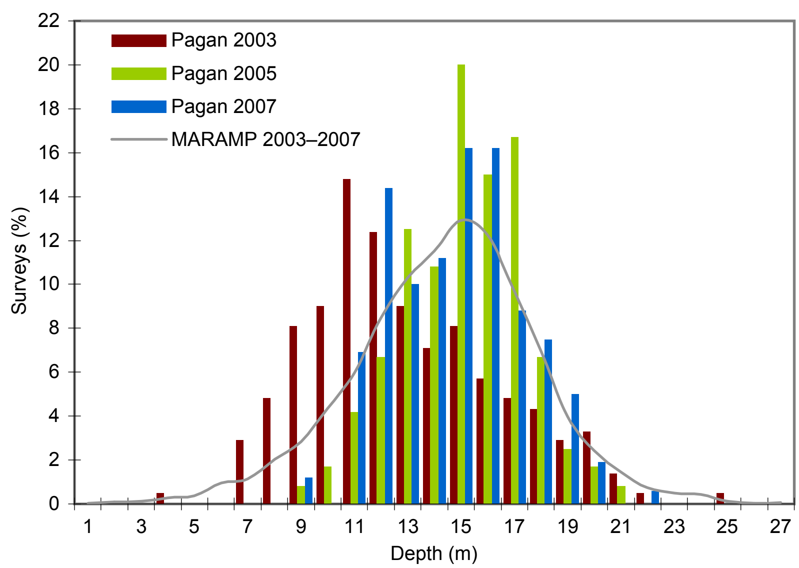
Table 13.2b. Numbers of oceanographic instruments deployed, shallow-water and deepwater CTD casts performed, and water samples collected around Pagan during MARAMP 2003, 2005, and 2007. Two types of instruments were moored around Pagan: sea-surface temperature (SST) buoy and subsurface temperature recorder (STR). Shallow-water CTD casts and water samples were conducted from the surface to a 30-m depth, and deepwater casts were conducted to a 500-m depth. Deepwater CTD cast information is presented in Chapter 3: "Archipelagic Comparisons."

Observation Type	Year						
Instruments	**2003**	**2005**		**2007**		**2009**	**Lost**
	Deployed	**Retrieved**	**Deployed**	**Retrieved**	**Deployed**	**Retrieved**	
SST	1	1	1	1	1	–	1
STR	1	1	1	1	3	3	–
CTD Casts	**2003**	**2005**		**2007**			**Total**
Shallow-water Casts	37	40		25			102
Deepwater Casts	–	9		1			10
Water Samples		**2005**		**2007**			**Total**
		5		7			12

Towed-diver Surveys: Depths

Figures 13.2b–e illustrate the locations and depths of towed-diver-survey tracks around Pagan and should be referenced when further examining results of towed-diver surveys from MARAMP 2003, 2005, and 2007.

Figure 13.2b. Depth histogram plotted from mean depths of 5-min segments of towed-diver surveys conducted on forereef habitats around Pagan during MARAMP 2003, 2005, and 2007. Mean segment depths were derived from 5-s depth recordings. Segments for which no depth was recorded were excluded. The grey line represents average depth distribution for all towed-diver surveys conducted around the Mariana Archipelago during MARAMP 2003, 2005, and 2007.



During MARAMP 2003, 21 towed-diver surveys were conducted along the forereef slopes around Pagan (Figs. 13.2b and c). The mean depth of all survey segments was 12.9 m (SD 1.7), and the mean depth of individual surveys ranged from 10.1 m (SD 2.9) to 16 m (SD 4.7).

During MARAMP 2005, 17 towed-diver surveys were conducted along the forereef slopes around Pagan (Figs. 13.2b and d). The mean depth of all survey segments was 15 m (SD 1), and the mean depths of individual surveys ranged from 12.5 m (SD 1.5) to 16.1 m (SD 2). Depths were not recorded for 4 surveys in the north region and for 1 survey in the west region because of an equipment malfunction.

During MARAMP 2007, 16 towed-diver surveys were conducted along the forereef slopes around Pagan (Figs. 13.2b and e). The mean depth of all survey segments was 14.8 m (SD 1.3), and the mean depths of individual surveys ranged from 12.6 m (SD 1.6) to 17.7 m (SD 3.1).

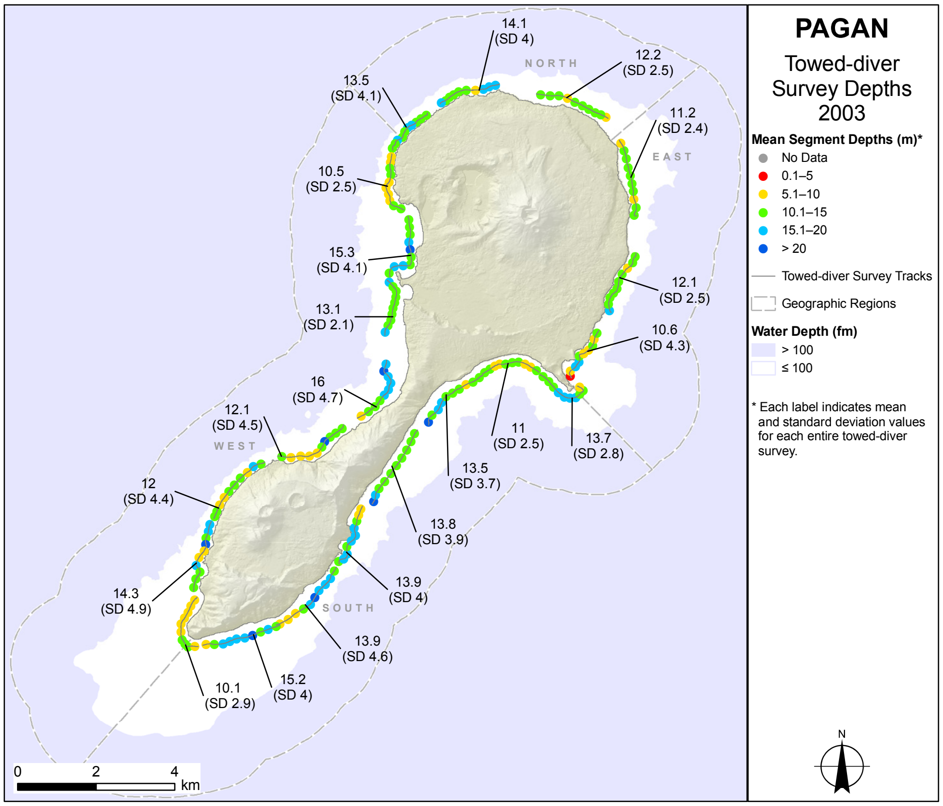


Figure 13.2c. Depth and tracks of towed-diver surveys conducted on forereef habitats around Pagan during MARAMP 2003. Towed-diver-survey tracks are color coded by mean depth for each 5-min segment. A black-text label shows the mean depth (and standard deviation) for each entire towed-diver survey. Each depth represents the depth of the benthic towboard during each survey; towboards are maintained nominally 1 m above the benthic substrate.

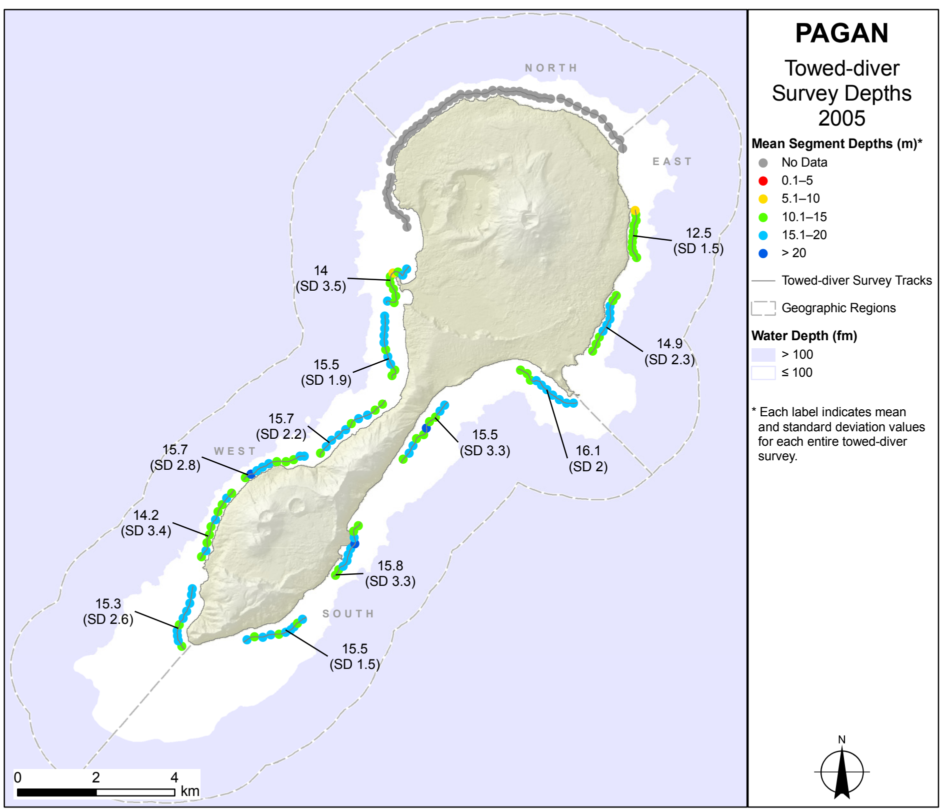
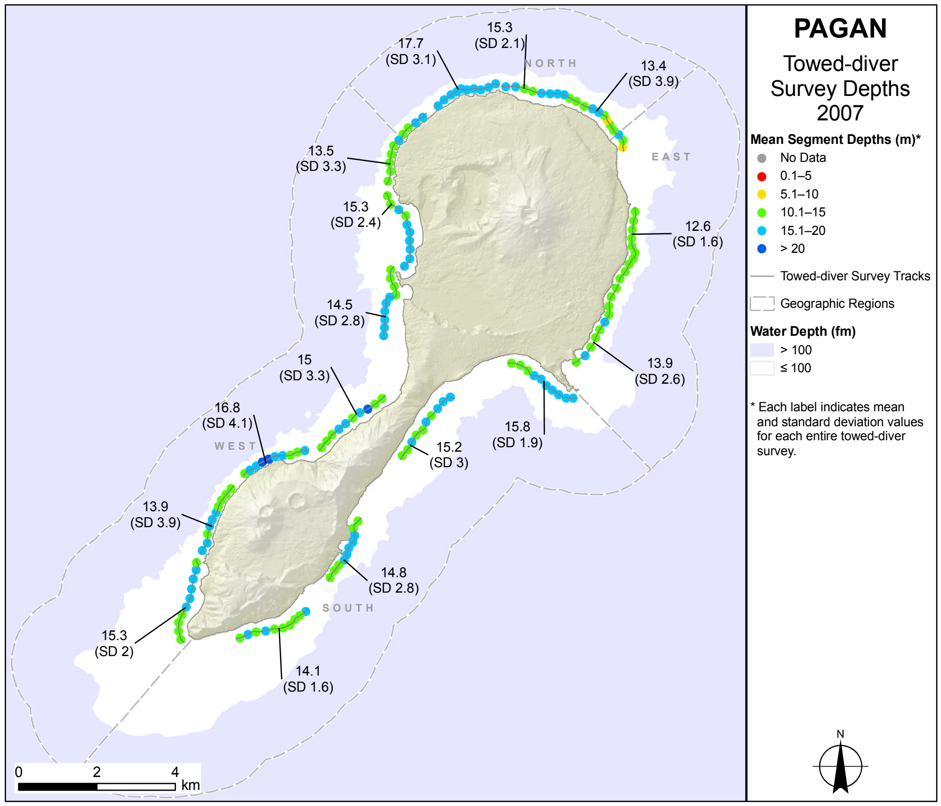


Figure 13.2d. Depths and tracks of towed-diver surveys conducted on forereef habitats around Pagan during MARAMP 2005. Towed-diver-survey tracks are color coded by mean depth for each 5-min segment. A black-text label shows the mean depth (and standard deviation) for each entire towed-diver survey. Each depth represents the depth of the benthic towboard during each survey; towboards are maintained nominally 1 m above the benthic substrate.

Figure 13.2e. Depths and tracks of towed-diver surveys conducted on forereef habitats around Pagan during MARAMP 2007. Towed-diver-survey tracks are color coded by mean depth for each 5-min segment. A black-text label shows the mean depth (and standard deviation) for each entire towed-diver survey. Each depth represents the depth of the benthic towboard during each survey; towboards are maintained nominally 1 m above the benthic substrate.



13.3 Benthic Habitat Mapping and Characterization

Benthic habitat mapping and characterization surveys around the island of Pagan were conducted during MARAMP 2003, 2005, and 2007 using acoustic multibeam sonar, underwater video and still imagery, and towed-diver observations. Acoustic multibeam sonar mapping provided bathymetric and backscatter data products over the depth range of ~ 7–2800 m with almost complete coverage around Pagan, except on the northeast corner. Coverage there began several hundred meters farther offshore than elsewhere as a result of rough sea conditions. Optical validation and benthic characterization, via diver observations and both video and still underwater imagery, were performed using towed-diver surveys and TOAD deployments conducted at depths of < 5–100 m.

13.3.1 Acoustic Mapping

Multibeam acoustic bathymetry and backscatter imagery (Fig. 13.3.1a) collected by the Coral Reef Ecosystem Division (CRED) around Pagan and Agrihan during MARAMP 2007 encompassed an area of 2511 km^2.

Multibeam bathymetry acquired around Pagan looks similar to the onshore topography of this island, which is dominated by Mount Pagan in the north and a second, smaller volcano in the south. The bathymetry reveals the steeply sloping flanks of Mount Pagan that descend from the coastline to depths > 2000 m. Numerous ridges and pinnacles are depicted by the bathymetry north of Pagan. Around southern Pagan, the seafloor topography is similar to the northern topography, with steep slopes that extend to depths > 3000 m, again punctuated with ridges and pinnacles. A large, shallow shelf area is shown around southern Pagan and extends for ~ 3 km from South Point (for place-names and their locations, see Figure 13.2a in Section 13.2: “Survey Effort”). East of Pagan around Sengao Peninsula, a smaller shelf area is shown, and wide channels on either side of this shelf are formed by ridges extending northeast and southeast. East of the narrow isthmus that joins the north and south of Pagan, another shelf is revealed, forming 1 of the 2 anchorage areas present at Pagan; the second is located west of the isthmus. Aside from these 3 shelf areas, there is little shallow seabed around Pagan.

Several distinctive features are revealed by the multibeam backscatter data acquired around Pagan. Around northern Pagan, the various ridges and pinnacles shown in the bathymetry were characterized by high-intensity backscatter, indicating hard substrates. High backscatter values also were observed along the shelf edge around southern Pagan. A large area of low-intensity backscatter, indicative of softer substrates, was present within and below the wide channel found south of Sengao Peninsula, suggesting this channel may form a conduit for the downward transport of soft sediments. Another large bay with low backscatter values lies north of the Bandera Peninsula, just downslope from 2 lakes formed in craters west of Mount Pagan, again suggesting a possible conduit for transport of sediments.

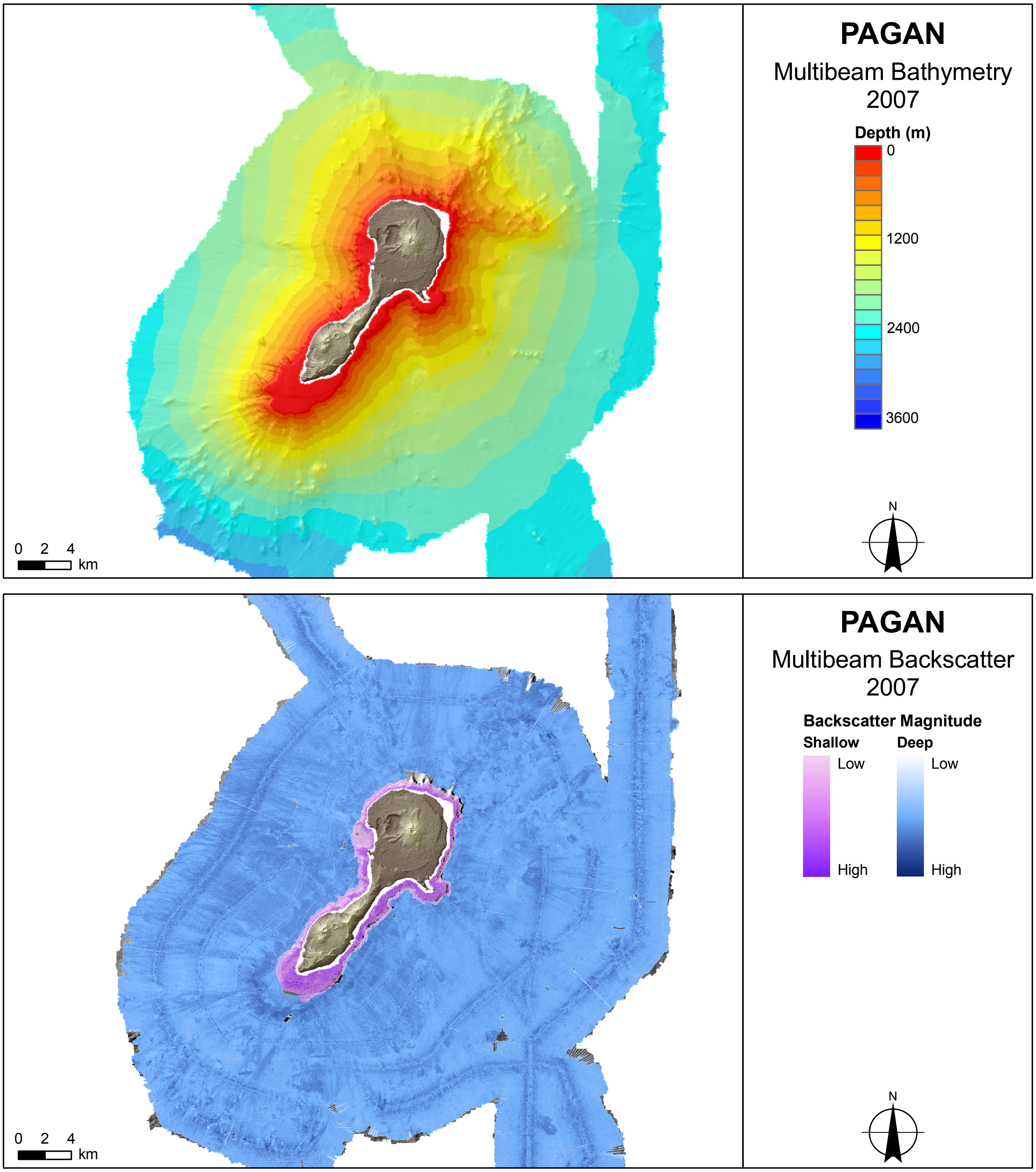


Figure 13.3.1a. Gridded (*top*) multibeam bathymetry (grid cell size: 60 m) and (*bottom*) backscatter (grid cell size: 5 m) collected around Pagan during MARAMP 2007 at depths of ~ 7–2800 m. Shallow-backscatter data (shown in purple) were collected using a 240-kHz Reson SeaBat 8101 ER sonar, and deep-backscatter data (shown in blue) were collected using a 30-kHz Kongsberg EM 300 sonar. Light shades represent low-intensity backscatter and may indicate acoustically absorbent substrates, such as unconsolidated sediment. Dark shades represent high-intensity backscatter and may indicate consolidated hard-bottom or coral substrates.

High-resolution Multibeam Bathymetry and Derivatives

High-resolution multibeam data collected in nearshore (depths of 0–800 m) waters around Pagan were combined into a grid at a 10-m resolution to allow for the identification of fine-scaled features (Fig. 13.3.1b). These high-resolution data were also used to derive maps of slope (Fig. 13.3.1c), rugosity (Fig. 13.3.1d), and bathymetric position index (BPI) zones (Fig. 13.3.1e). Together, these maps provide layers of information to characterize the benthic habitats around Pagan.

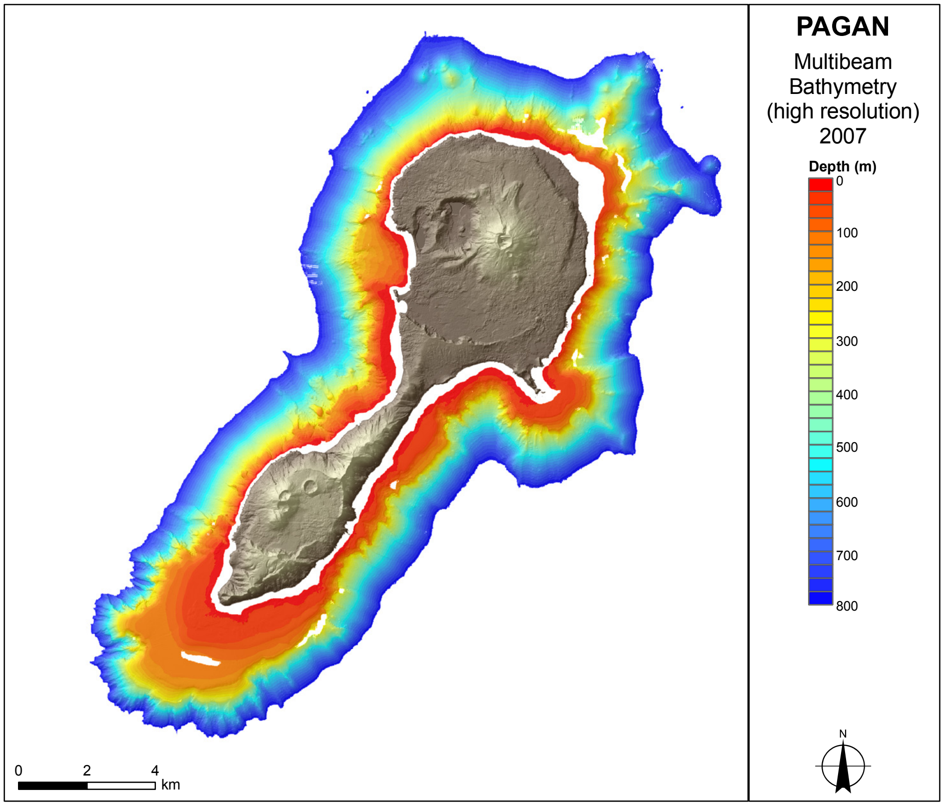


Figure 13.3.1b. High-resolution multibeam bathymetry collected by CRED around Pagan during MARAMP 2007. This 10-m bathymetry grid, clipped at 800 m, is used as the basis for slope, rugosity, and BPI derivatives.

The high-resolution multibeam bathymetry north of Pagan reveals a predominantly smooth seabed, characterized by moderate to steep slopes. The steepest slopes are found toward the east, where slopes > 50° are observed along the edge of shelf and ridge features and around a number of cones that are shown north of Pagan at a depth of 500–700 m (Fig. 13.3.1c). These topographic features also support the highest levels of rugosity (Fig. 13.3.1d). The BPI terrain analysis supports these observations and indicates that "slopes" are the dominant zone in this area (Fig. 13.3.1e).

East of Pagan, the high-resolution bathymetry reveals a similarly steeply sloping seafloor, although additional topographic complexity is provided by the numerous ridges that extend from the flanks of Mount Pagan. Observed slopes were generally 15°–20°, although very steep slopes > 50° were present at around a depth of 140–160 m. Additional steep slopes > 50° were observed on either side of the narrow ridges, which also support the highest levels of rugosity. BPI analysis highlights the complex nature of the seafloor in this area, which is characterized by a mixture of slopes, crests, and depressions.

South of Pagan, the seabed character is somewhat different from the one in the north, and the bathymetry data show a series of shallow shelves, with successively deeper areas of flat seabed at depths down to 150 m. The shelf area around the Sengao Peninsula on the eastern shore has a depth of ~ 40 m and extends along the coast toward Fuwaebosu. Slope, rugosity, and BPI analyses suggest that the shelf is smooth and flat. Below the shelf, the slope and BPI zone maps reveal that the seabed is moderately sloping down to a depth of 130–140 m, at which point it becomes steeper with slopes > 50°. The seabed descends steeply, forming ridges and canyons in several places, most noticeably north and south of the Sengao Peninsula.

Around South Point, the seabed is characterized by the presence of an extensive, shallow shelf, which extends for nearly 3 km out from South Point and is composed of 2 terraces at depths of ~ 50 and 125 m. Both terraces are low-rugosity, flat zones. High-resolution bathymetry and slope maps show mound-like features on this shallow shelf, features that may indicate coral reef habitats (Fig. 13.3.1c). No optical data were obtained in this area to validate this hypothesis, and further investigation of this area is merited. Below this shelf, the seabed is characterized by highly rugose slopes > 50°, with steep-sided ridges forming canyons.

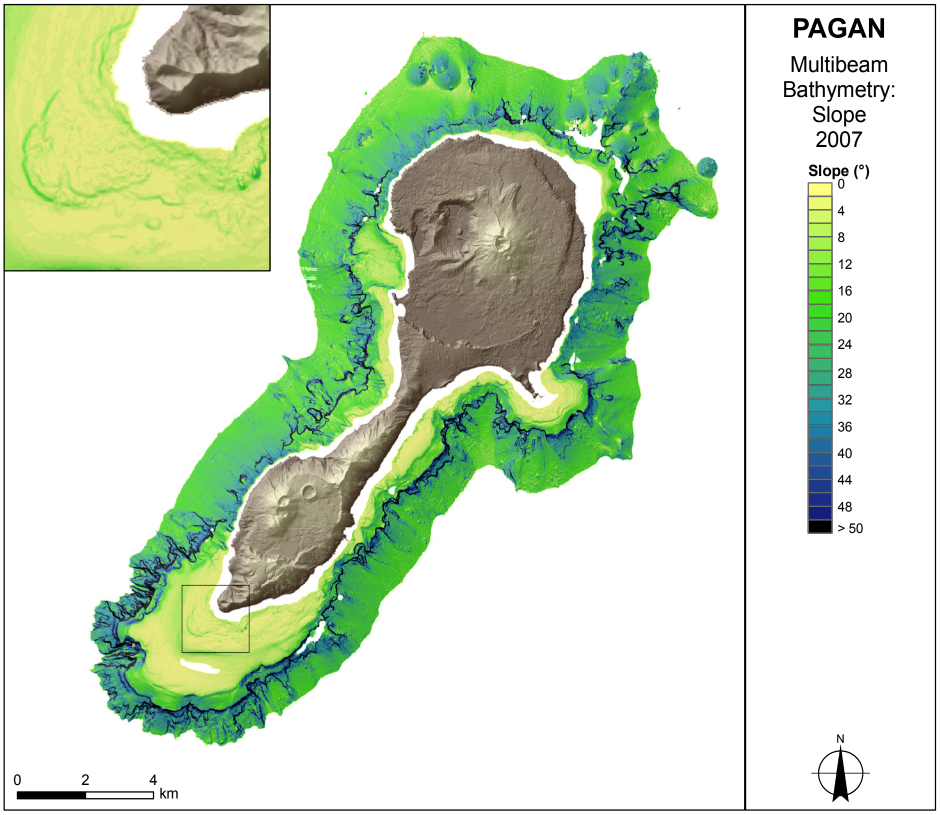


Figure 13.3.1c. Slope (°) of 10-m bathymetric grid around Pagan. Derived from data collected in 2007, this map reflects the maximum rate of change in elevation between neighboring cells with the steepest slopes shown in the darkest shades of blue and the flattest areas in yellow shades. Inset map shows complex bathymetry at a depth of 15–40 m on the shelf around South Point.

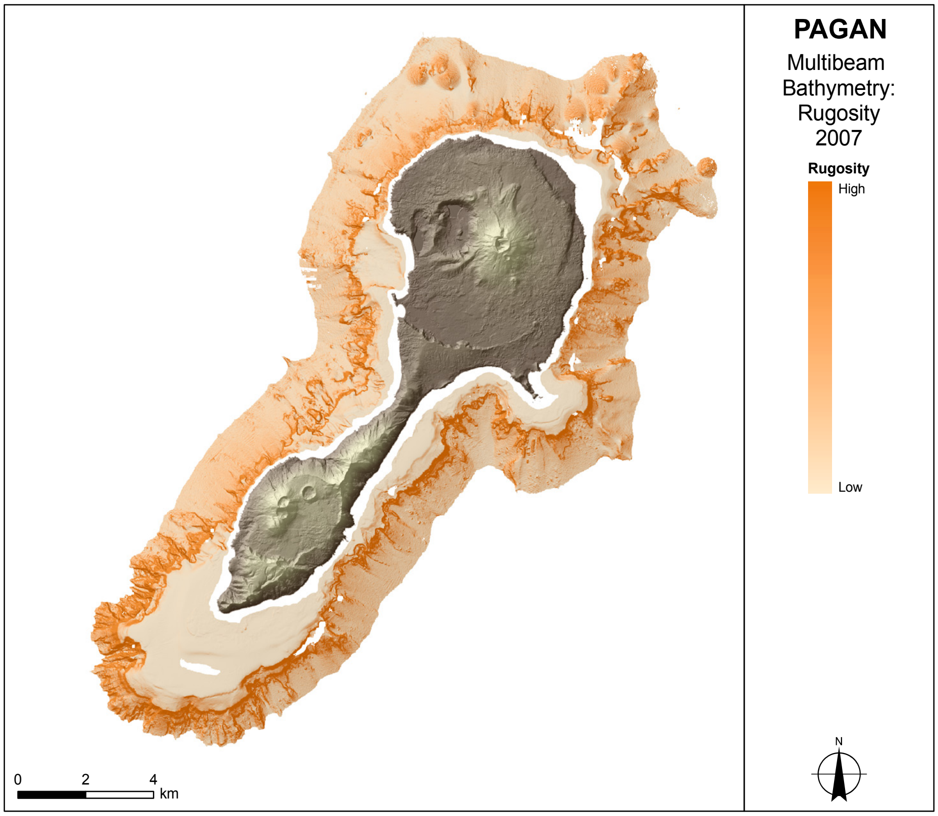


Figure 13.3.1d. Rugosity of 10-m bathymetric grid around Pagan. Derived from data collected in 2007, these rugosity values are a measure of the ratio of surface area to planimetric area within a given cell's neighborhood and indicate topographic roughness.

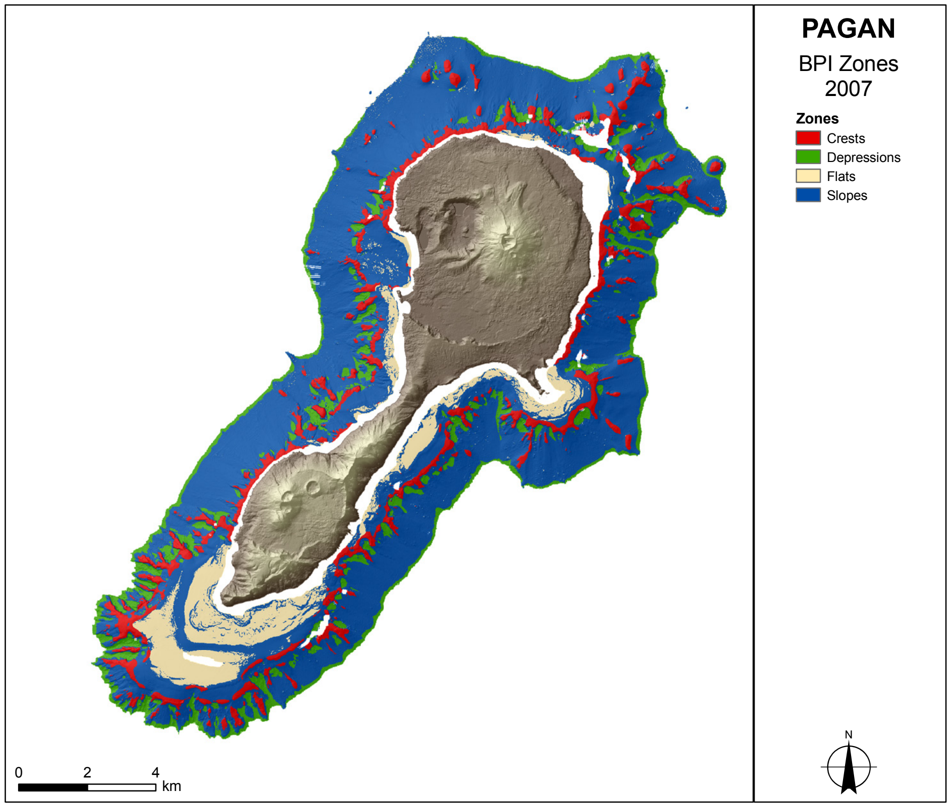


Figure 13.3.1e. BPI zones of 10-m bathymetric grid around Pagan derived from data collected in 2007. BPI is a second-order derivative of bathymetry that evaluates elevation differences between a focal point and the mean elevation of the surrounding cells within a user-defined circle. Four BPI Zones—crests, depressions, flats, and slopes—were used in this analysis.

West of Pagan, narrow shelves are present within Apaan Bay and north of Bandera Peninsula. The shelf north of Bandera Peninsula is bordered by a large area of gentle slopes and flats, forming a large bay. Below these shelf areas, the seabed topography is similar to elsewhere around Pagan, with moderate slopes at depths < 200 m, a zone of very steep slopes (> 50°) at depths of 200–250 m, and then a steeply sloping seabed at depths > 250 m.

High-resolution Multibeam Backscatter and Derivatives

The quality of the backscatter data acquired around Pagan was impacted to some extent by the very steep slopes present around much of this island, and time constraints that resulted in data being acquired at speeds slightly faster than the optimum rate. These issues resulted in some loss of data quality, such as gaps in the data coverage. Despite these constraints, the high-resolution data do provide some clear patterns in the acoustic characteristics of the seabed around this island (Fig. 13 3.1f) that can be related to other seabed characteristics such as topography and slope.

North and east of Pagan, high backscatter values are shown in the shallowest areas (Fig. 13 3.1f), and lower backscatter values are shown below the shelf break, which is demarcated by the narrow band of steeply (> 50°) sloping seabed. These backscatter data and the hard–soft classification (Fig. 13.3.1g) suggest that soft sediments are present on the deeper slopes and hard substrates are present on the shallow flats and slopes, although the backscatter intensity may be influenced to some degree by the slopes themselves, vessel speed, or the instrument settings during data collection.

South and east of Pagan, higher backscatter values indicate hard substrates for the shallow shelf areas around Sengao Peninsula, along the southeast coast, and near South Point. These results show the importance of the extensive shelf around South Point that provides a suitable substrate to support coral reef habitat. Below this shelf, the sloping seabed has predominantly low backscatter values, suggesting that soft substrates might be present there.

Along the southeastern coast of Pagan, the hard–soft classification map shows several small areas of soft sediments associated with valleys in the seabed. An area of soft sediment is indicated by low backscatter values along the inner margin of a shallow shelf, adjacent to the reef edge, and along the more gradually sloping base.

Southwest of Pagan, backscatter values are predominantly low, suggesting the predominance of soft substrates. Shallow shelves, where hard substrates tend to be found, were not observed in this area. In contrast, west of Pagan, around Apaan

Bay, high backscatter values are shown along a shallow shelf area. The hard–soft map shows patches of soft sediments that correspond to channels revealed in the multibeam bathymetry. The accumulation of sediment in these areas may relate to sediment inputs from surface-water runoff from this volcanic island. The hard–soft analysis also suggests areas of soft

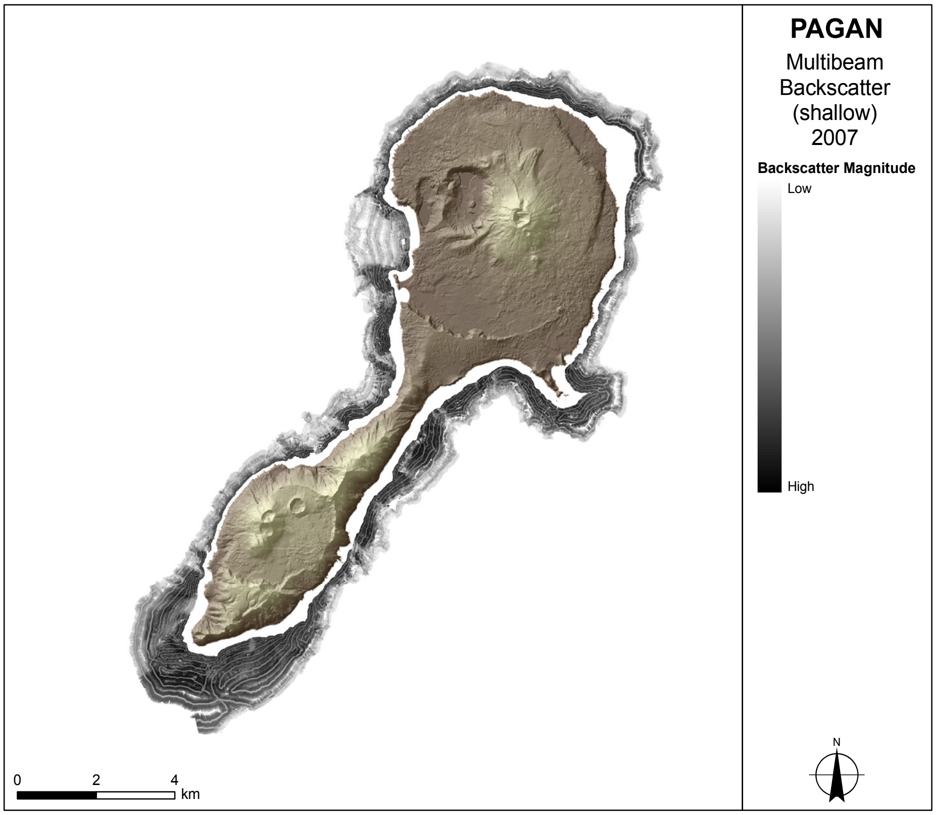


Figure 13.3.1f. Gridded, high-resolution, multibeam backscatter data (grid cell size: 10 m) collected around Pagan during MARAMP 2007. Light shades represent low-intensity backscatter and may indicate acoustically absorbent substrates. Dark shades represent high-intensity backscatter and may indicate consolidated hard-bottom and coral substrates.

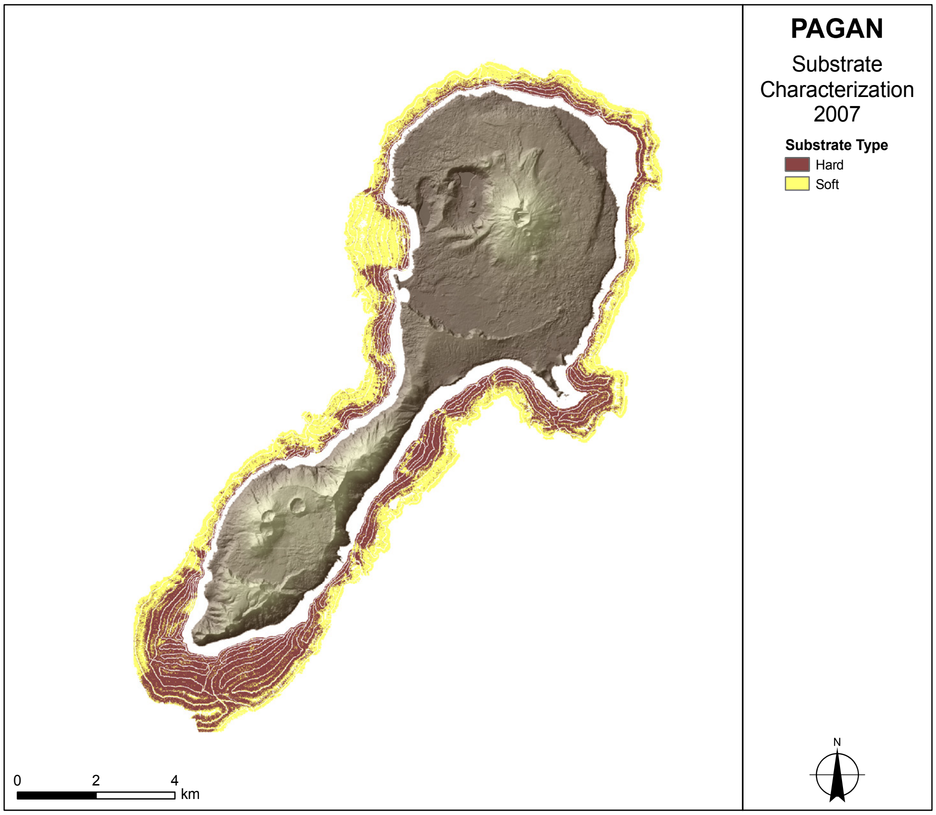


Figure 13.3.1g. Hard and soft substrates (grid cell size: 10 m) based upon an unsupervised classification of multibeam bathymetry and backscatter data acquired around Pagan in 2007. Data cannot be collected directly under the ship, hence the white lines showing the ship's path.

sediments within the small bay south of Bandera Peninsula and the larger bay to the north. Onshore, adjacent to this larger bay, 2 lakes are present within the maar, a shallow, flat-floored crater created by explosive volcanic eruptions shown on the topographic maps, west of Mount Pagan. The lower of these 2 lakes, Lagona Lake, is only tens of meters away from shore and may contribute soft sediments to the bay below.

13.3.2 Optical Validation

During MARAMP 2003, 8 TOAD optical-validation surveys were conducted at Pagan at depths < 100 m (Fig. 13.3.2a). Subsequent analyses of video acquired from these surveys provided estimates of the percentages of sand cover and live-hard-coral cover.

Covering a distance of 103 km at depths of 4–25 m, 54 towed-diver optical-validation surveys of forereef habitats, were conducted around Pagan during MARAMP 2003, 2005, and 2007. At 5-min intervals within each survey, divers recorded percentages of sand cover and live-hard-coral cover and habitat complexity using a 6-level categorical scale from low to very high.

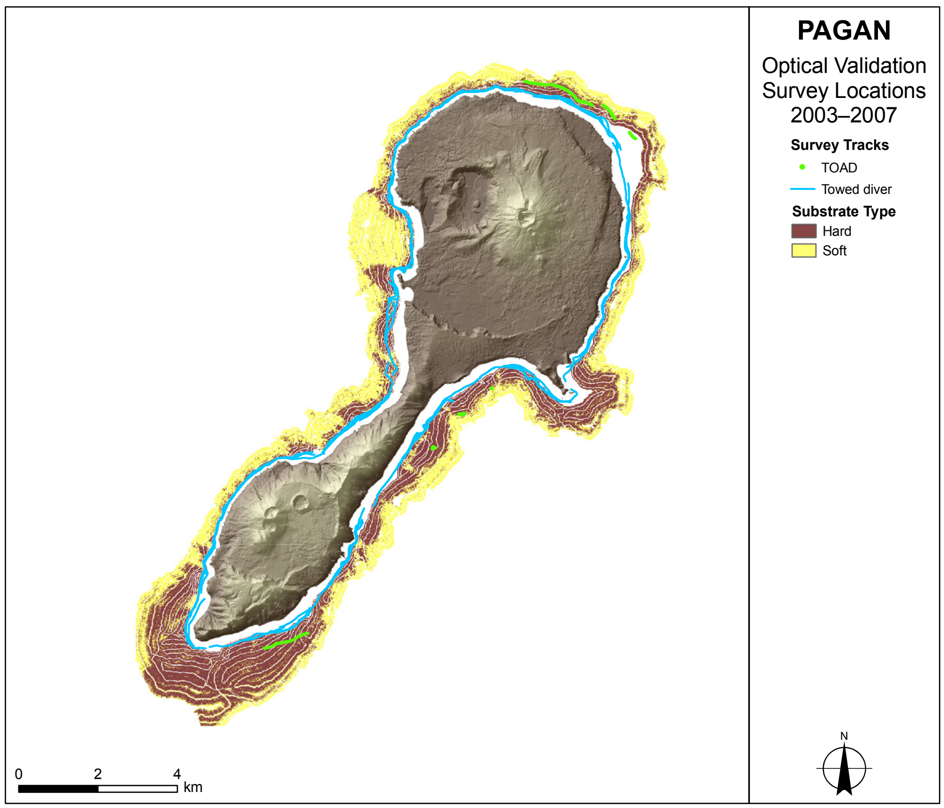


Figure 13.3.2a. Towed-diver tracks from surveys of forereef habitats conducted around Pagan during MARAMP 2003, 2005, and 2007, and TOAD camera-sled tracks for MARAMP 2003. Survey tracks are displayed over the multibeam hard–soft substrate map. Data cannot be collected directly under the ship, hence the white lines showing the ship's path.

13.3.3 Habitat Characterization

Sand cover, habitat complexity, and live coral cover around Pagan are discussed in this section. These descriptions are organized by the 4 geographic regions around Pagan. Optical-validation surveys conducted around Pagan during MARAMP 2003, 2005, and 2007 showed clear differences between the seabed surveyed around the northern and eastern flanks of Mount Pagan, the southern and western flanks of Mount Pagan, the narrow central region of Pagan, and South Point. In general, habitats in the north and east regions consisted of hard substrates (Fig. 13.3.3a), were fairly complex (Fig. 13.3.3b), and supported a moderate cover of live corals (Fig. 13.3.3c). In contrast, south and west of Mount Pagan, the seabed was characterized by low-complexity, soft-sediment habitats that supported very low levels of live coral cover. On either side of the narrow center of Pagan, habitats were hard substrate of medium complexity with moderate amounts of live coral cover. Around South Point, sand was again more common, and habitat complexity was lower than in other areas around this island. Overall, live coral cover around Pagan was low to medium compared to the rest of the Mariana Archipelago, with the highest concentrations of live coral cover observed at the tip of Sengao Peninsula on the east side of this island. These general conclusions are discussed in more detail in the rest of this section.

In the north region, predominantly hard substrates with low sand cover were observed during towed-diver surveys. In the western half of this geographic region, very low sand cover was recorded, and the habitats encountered were characterized by medium to high complexity and live coral cover of 10.1%–30%. In the eastern half, sand cover was higher, reaching 75.1%–100% in one small area. Habitat complexity there was lower than in the western half, and live coral cover was also lower, generally ranging from 1.1%–20%. The habitats present included spur-and-groove reefs, slopes, ridges, hard pavement, and boulders. Optical data collected in deeper water (depths of 50–100 m) using the TOAD suggest mainly hard substrates, with a section of 100% sand cover northeast of Tarage in the north region. Very low live coral cover was recorded at these depths, with only isolated video frames showing live corals.

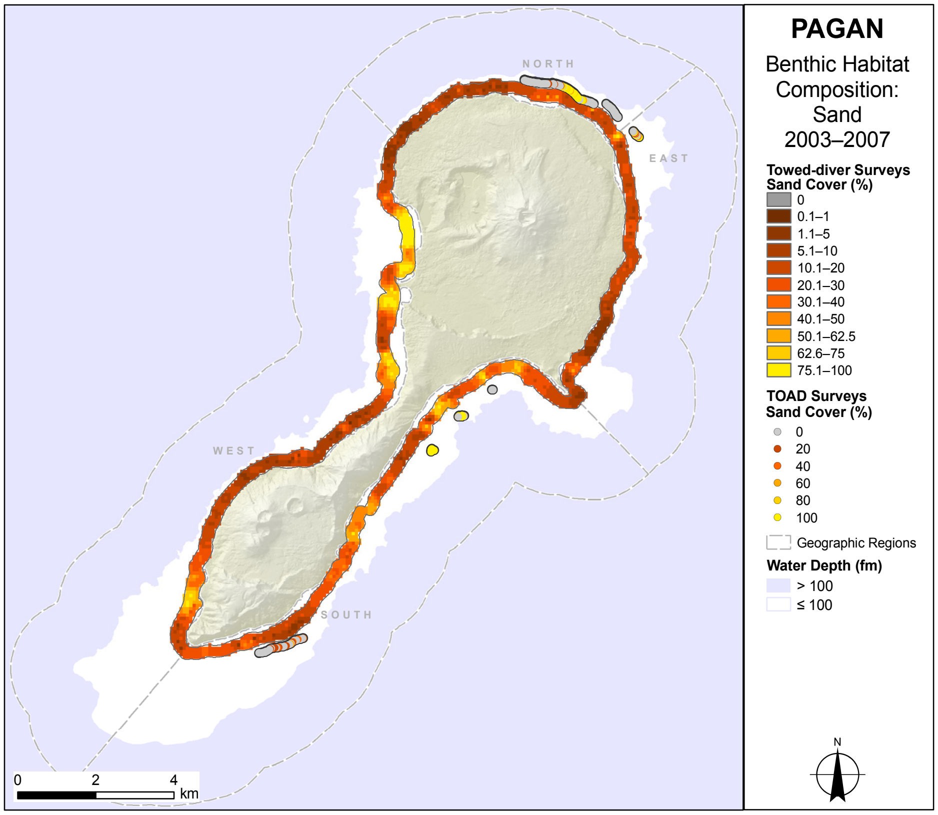


Figure 13.3.3a. Observations of sand cover (%) from towed-diver surveys of forereef habitats conducted and analysis of TOAD video collected around Pagan during MARAMP 2003, 2005, and 2007.

Towed-diver surveys suggest that habitats in the east region had slightly more sand than areas farther north, with cover generally in a range of 5.1%–20%. Habitat complexity was predominantly medium to high, and live coral cover of 5.1%–40% was observed. Habitats encountered were described as a mixture of spur-and-groove reef, rocky reef, and pavement, with boulders frequently forming part of the habitat. Results from the single short TOAD survey conducted in this region suggested patchy sand cover and very few live corals, although 2 video frames showed live corals at depths of ~ 55 and 80 m.

In the south region, sand was a more dominant component of the seabed habitat with high cover recorded around Degusa and east of Buritoma. TOAD surveys also documented high cover of sand offshore from Apansantate, although this area is classified as hard substrate in the hard–soft map (Fig. 13.3.1g), suggesting that the sand is likely to be a thin veneer with acoustically reflective substrates beneath. Based on towed-diver surveys, habitat complexity in this area was low to medium, but live coral cover was not very dissimilar to the more complex habitats encountered north of Pagan. Live coral cover from towed-div surveys was variable, with cover of up to 40% recorded in several locations. Analyses of video footage obtained in deeper water during TOAD surveys indicate very few live corals, with cover of 20% in some video frames at depths up to ~ 75 m. Habitats observed in this region included pavement flats, patch reefs, boulders in sand, and continuous reefs.

Around South Point, towed-diver surveys suggested some variability in the distribution of sand cover. High sand cover was recorded in the narrow bay just north of South Point (Fig. 13.3.3a), corresponding to a sand channel identified in the hard–soft substrate map (Fig. 13.3.1g). Hard substrates were recorded at South Point itself and at Piarama, both in the shallow waters surveyed by towed divers and in the slightly deeper waters surveyed with the TOAD. Towed-diver surveys conducted around South Point revealed habitats of medium to medium-high complexity and generally low live coral cover of 1.1%–30%. Analyses of video footage acquired during TOAD surveys indicate very low live coral cover at a depth of 30–40 m, with a small number of video frames showing 20% live coral cover.

Figure 13.3.3b. Observations of benthic habitat complexity from towed-diver surveys of forereef habitats conducted around Pagan during MARAMP 2003, 2005, and 2007.

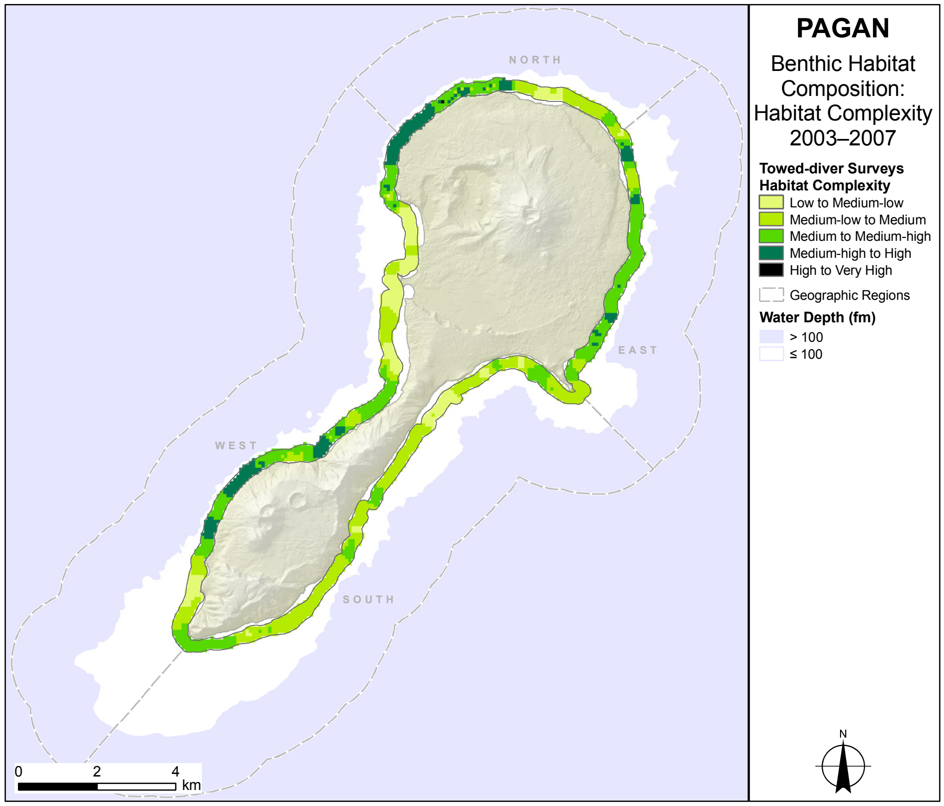
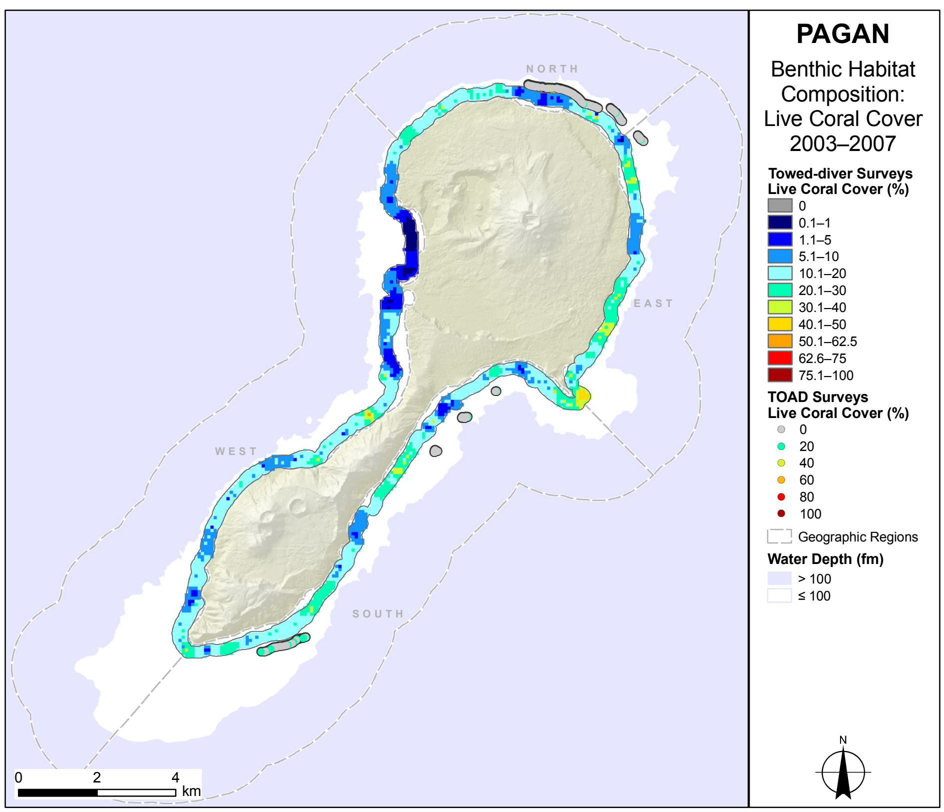


Figure 13.3.3c. Cover (%) observations of live hard corals from towed-diver surveys of forereef habitats conducted and analysis of TOAD video collected around Pagan during MARAMP 2003, 2005, and 2007.



Around southwestern Pagan, around the flanks of the southern volcano and on either side of the narrow isthmus of Pagan, habitats observed during towed-diver surveys were characterized by predominantly hard substrates of medium to high complexity and in general supported live coral cover of 1.1%–20%, with cover of up to 40% recorded in one location.

The seabed observed on the southwestern flanks of Mount Pagan was somewhat different than the one seen on the northern and eastern flanks, as it was predominantly sandy, with very low live coral cover and low to medium habitat complexity. Towed-diver surveys conducted within the bays north and south of Bandera Peninsula suggest habitats characterized by high cover of sand and very low cover of live corals. These corresponded to areas of soft sediment identified on the hard–soft substrate map (Fig. 13.3.1g).

13.4 Oceanography and Water Quality

13.4.1 Hydrographic Data

2003 Spatial Surveys

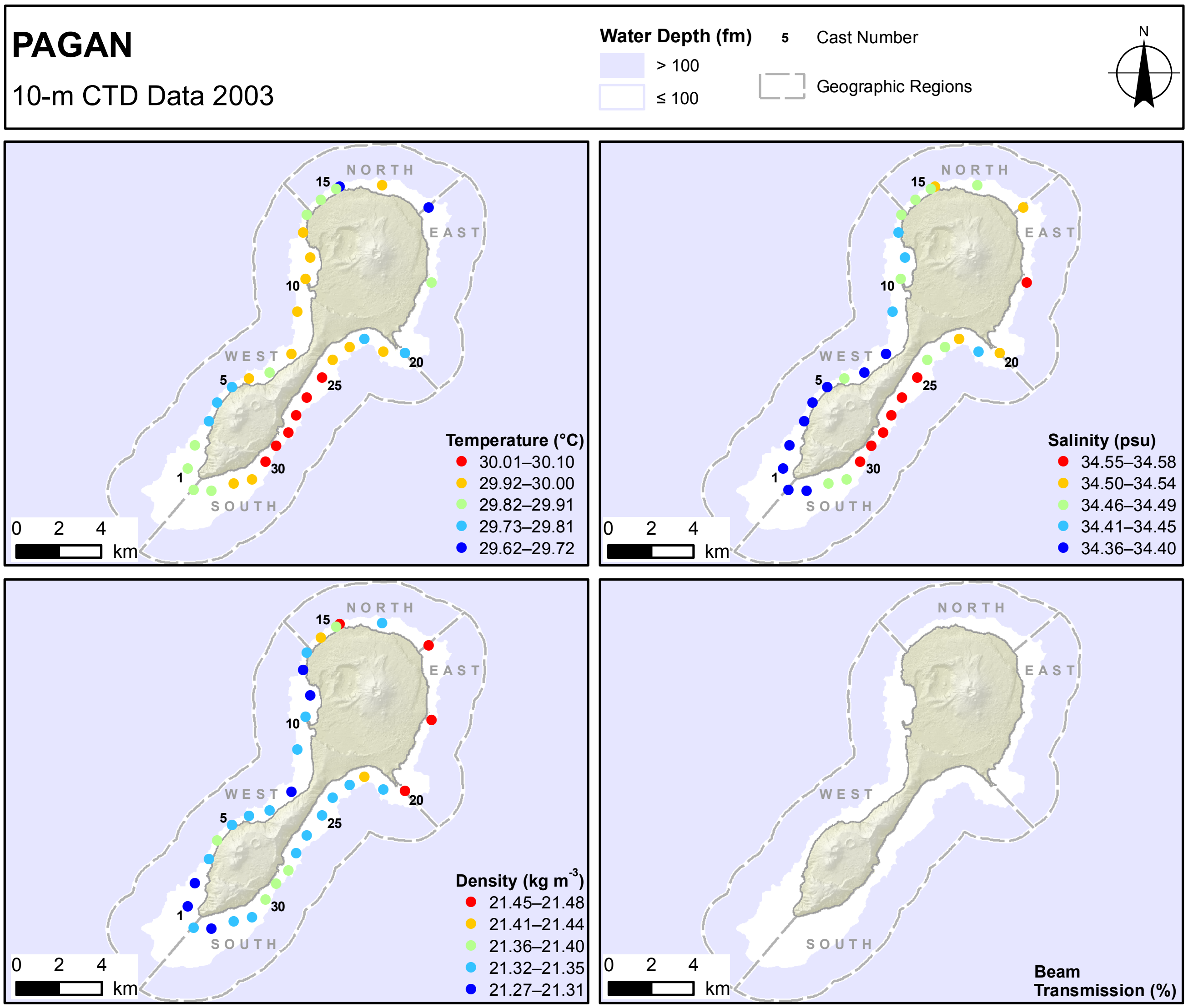


Figure 13.4.1a. Values of (*top left*) water temperature, (*top right*) salinity, and (*bottom left*) density at a 10-m depth from shallow-water CTD casts around Pagan during MARAMP 2003, with casts 20 and 22 done on August 25, casts 16–19 done on August 26, casts 13–15 done on September 6, casts 1–12 done on September 7, casts 21, 23, 24, and 31–34 done on September 8, and casts 25–30 done on September 12.

During MARAMP 2003, shallow-water conductivity, temperature, and depth (CTD) casts were conducted in nearshore waters around the island of Pagan over the period of August 25–September 12. Temperature, salinity, and density values from 34 of these casts varied both spatially and vertically around this island. Spatial comparisons of water properties at a depth of 10 m suggest moderate variability around this island, with temperature differences measured up to 0.48°C (Fig. 13.4.1a). The warmest temperature (30.1°C) and highest salinity (34.58 psu) values were recorded in the south region (casts 25–30). Vertical comparisons of CTD profiles reveal water properties with a broad range in temperature (1.3°C), salinity (0.7 psu), and density (0.7 kg m^{-3}) values (Fig. 13.4.1b). These large ranges could have resulted from temporal separation in sampling. These measured ranges in water properties also could result from enhanced mixing, with deeper waters or localized upwelling observed in the east region (cast 18) relative to other areas of this island. Additionally, a well-mixed and warm (30.1°C) water column was seen in the south region (casts 25–30).

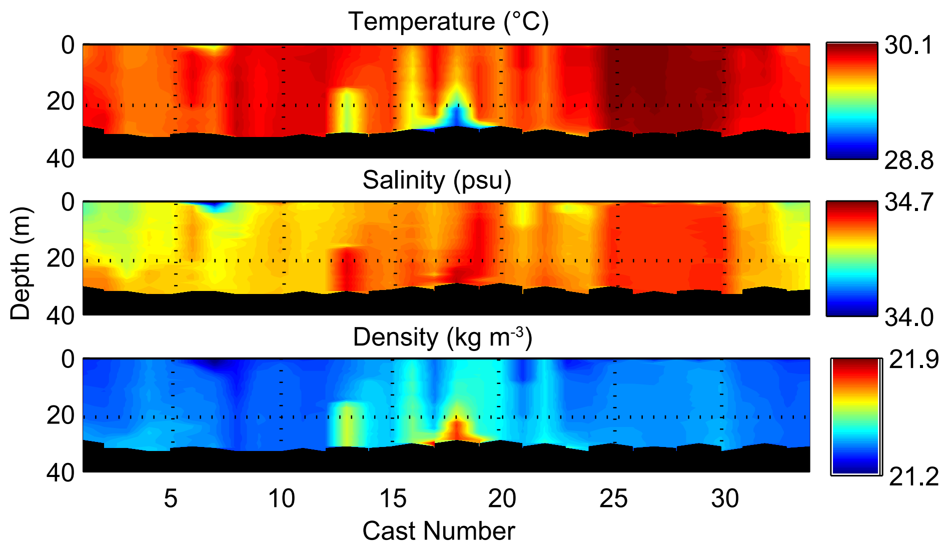


Figure 13.4.1b. Shallow-water CTD cast profiles to a 30-m depth around Pagan during MARAMP 2003, August 25–26, September 6–8, and September 12, including temperature (°C), salinity (psu), and density (kg m^{-3}). Profiles, shown sequentially in a left-to-right direction in this graph, correspond to cast locations that are numbered sequentially 1–34 in a clockwise direction around Pagan. Casts 20 and 22 were completed on August 25, casts 16–19 were done on August 26, casts 13–15 were done on September 6, casts 1–12 were done on September 7, casts 21, 23, 24, and 31–34 were done on September 8, and casts 25–30 were done on September 12. For cast locations and numbers around this island in 2003, see Figure 13.4.1a.

2005 Spatial Surveys

During MARAMP 2005, shallow-water CTD casts were conducted in nearshore waters around Pagan over the period of September 6–8. Temperature, salinity, density, and beam transmission values from 39 of these casts varied both spatially and vertically around this island. Spatial comparisons of water properties at a depth of 10 m suggest low variability around Pagan, with temperature differences measured up to 0.31°C (Fig. 13.4.1c). Cool (28.77°C–28.83°C) waters were recorded in the south region (casts 32–39), with low salinity (34.29–34.38 psu), low density (21.61–21.66 kg m^{-3}), and high beam transmission (> 94.19%) values compared to waters monitored at other cast locations at Pagan. Vertical comparisons of CTD profiles (Fig. 13.4.1d) reveal a well-mixed water column in most cast locations; however, at select locations, the water column was highly stratified (casts 29–31). Additionally, a cold, less saline and clear (low beam transmission) water mass was observed at the upper surface southeast of Pagan (casts 34–39), likely indicative of a rain event that occurred during data collection.

Water samples were collected in concert with shallow-water CTD casts at 5 select locations at Pagan in 2005 to assess water-quality conditions. The following ranges of measured parameters were recorded: chlorophyll-*a* (Chl-*a*), 0.125–0.225 µg L^{-1}; total nitrogen (TN), 0.084–0.226 µM; nitrate (NO_3^-), 0.069–0.205 µM; nitrite (NO_2^-), 0.014–0.021 µM; phosphate (PO_4^{3-}), 0.022–0.04 µM; and silicate [$Si(OH)_4$], 1.364–1.705 µM. Concentrations of Chl-*a* were highest in the north and west regions, whereas total nitrogen, nitrate, and nitrite were greatest in the south region (Fig. 13.4.1e). Silicate and phosphate varied concurrently, with higher values measured to the north and lower values to the south.

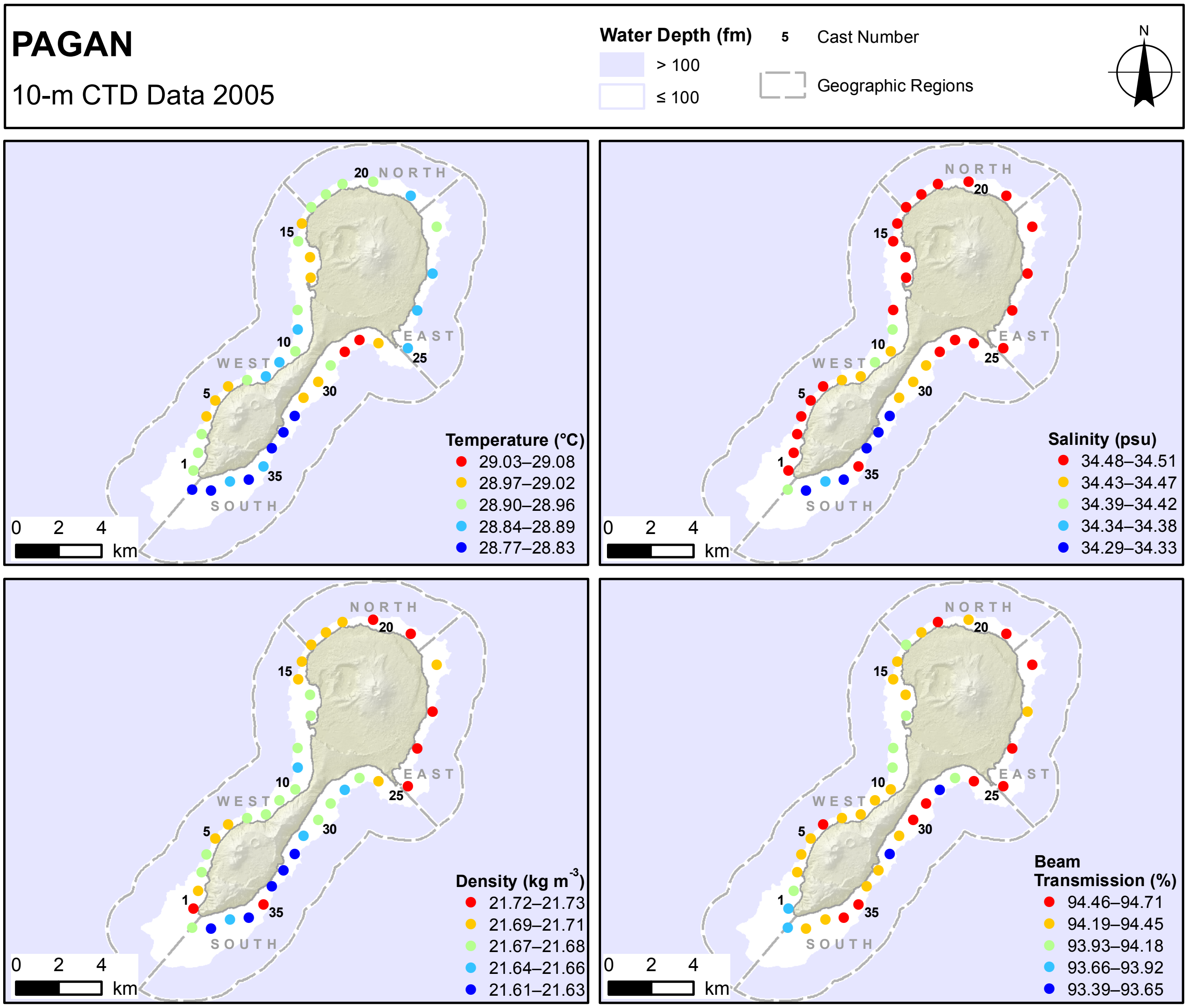
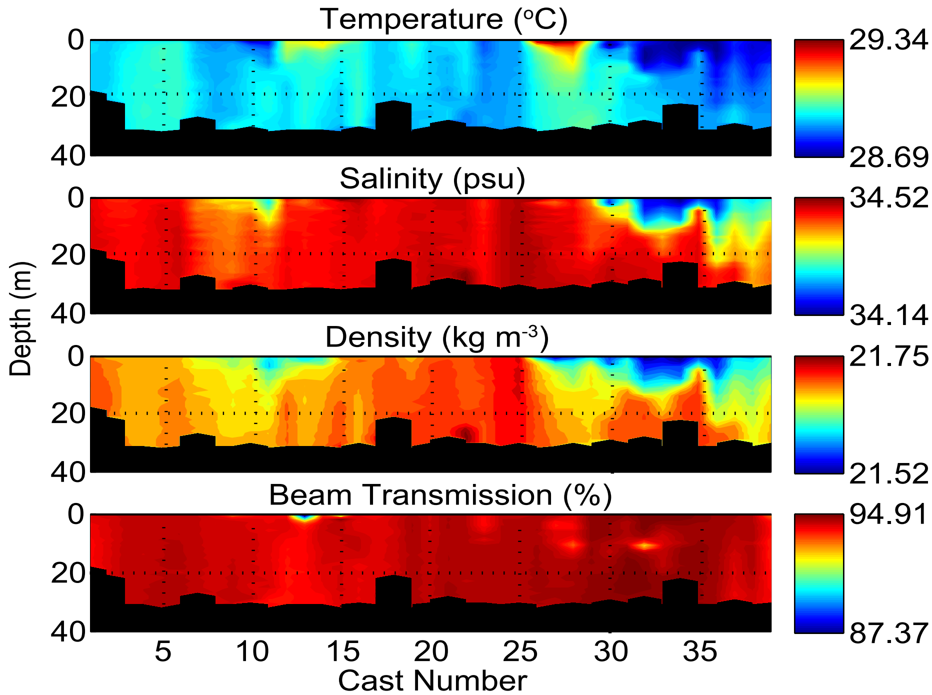


Figure 13.4.1c. Values of (*top left*) water temperature, (*top right*) salinity, (*bottom left*) density and (*bottom right*) beam transmission at a 10-m depth from shallow-water CTD casts around Pagan on September 6–8 during MARAMP 2005.

Figure 13.4.1d. Shallow-water CTD cast profiles to a 30-m depth around Pagan on September 6–8 during MARAMP 2005, including temperature (°C), salinity (psu), density (kg m^{-3}), and beam transmission (%). Profiles, shown sequentially in a left-to-right direction in this graph, correspond to cast locations that are numbered sequentially 1–39 in a clockwise direction around Pagan. For cast locations and numbers around this island in 2005, see Figure 13.4.1c.



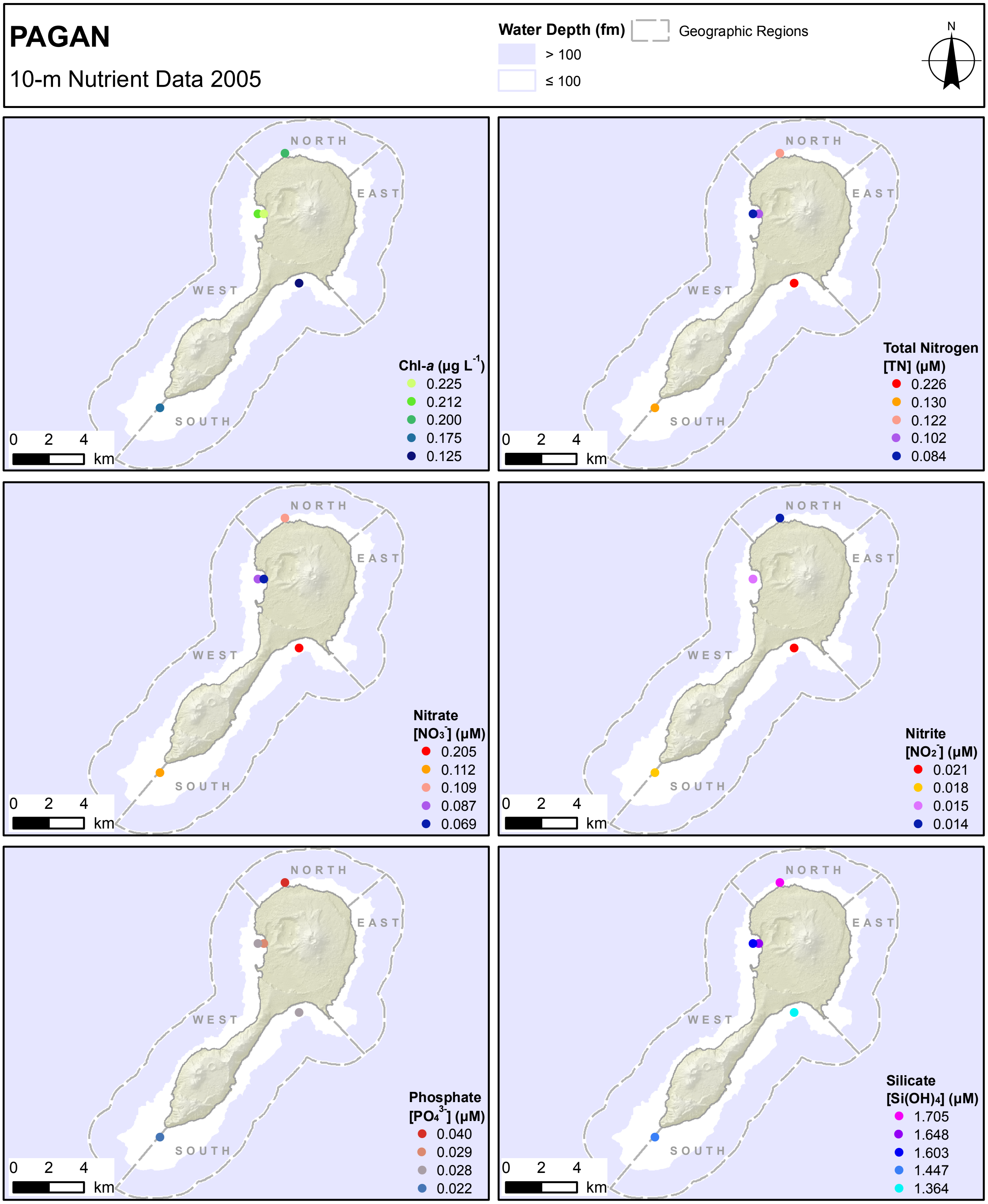


Figure 13.4.1e. Concentrations of (*top left*) Chl-*a*, (*top right*) total nitrogen, (*middle left*) nitrate, (*middle right*) nitrite, (*bottom left*) phosphate, and (*bottom right*) silicate at a 10-m depth, from water samples collected at Pagan on September 6–8 during MARAMP 2005.

2007 Spatial Surveys

During MARAMP 2007, shallow-water CTD casts were conducted in nearshore waters around Pagan over the period of June 4–6. Temperature, salinity, density, and beam transmission values from 23 of these casts varied both spatially and vertically around this island. Spatial comparisons of water properties at a depth of 10 m suggest moderate variability around Pagan, with temperature differences measured up to 0.6°C (Fig. 13.4.1f). Warm (29.77°C) water was recorded in the west region (casts 1–3), with low salinity (34.49 psu), low density (21.46 kg m^{-3}), and high beam transmission (92.25%) values compared to waters monitored at other cast locations at Pagan. In general, waters surrounding the west and north regions were warmer than waters in the east and south regions. Vertical comparisons of CTD profiles reveal water properties with a broad range in water temperature (1.3°C) and moderate ranges in salinity (0.3 psu), density (0.6 kg m^{-3}), and beam transmission (1.7%) values (Fig. 13.4.1g). The observed ranges in temperature and salinity values may result from enhanced mixing with deeper waters or localized upwelling seen at discrete locations around this island (casts 5, 6–8, 13–17).

Water samples were collected in concert with shallow-water CTD casts at select locations at Pagan in 2007 to assess water-quality conditions. The following ranges of measured parameters were recorded: Chl-*a*, 0.028–0.307 µg L^{-1}; total nitrogen (TN), 0.023–0.133 µM; nitrate (NO_3^-), 0.004–0.104 µM; nitrite (NO_2^-), 0.019–0.029 µM; phosphate (PO_4^{3-}), 0.034–0.043 µM; and silicate [$Si(OH)_4$], 1.999–2.463 µM. Based on data from 6 sample locations, the highest concentra-

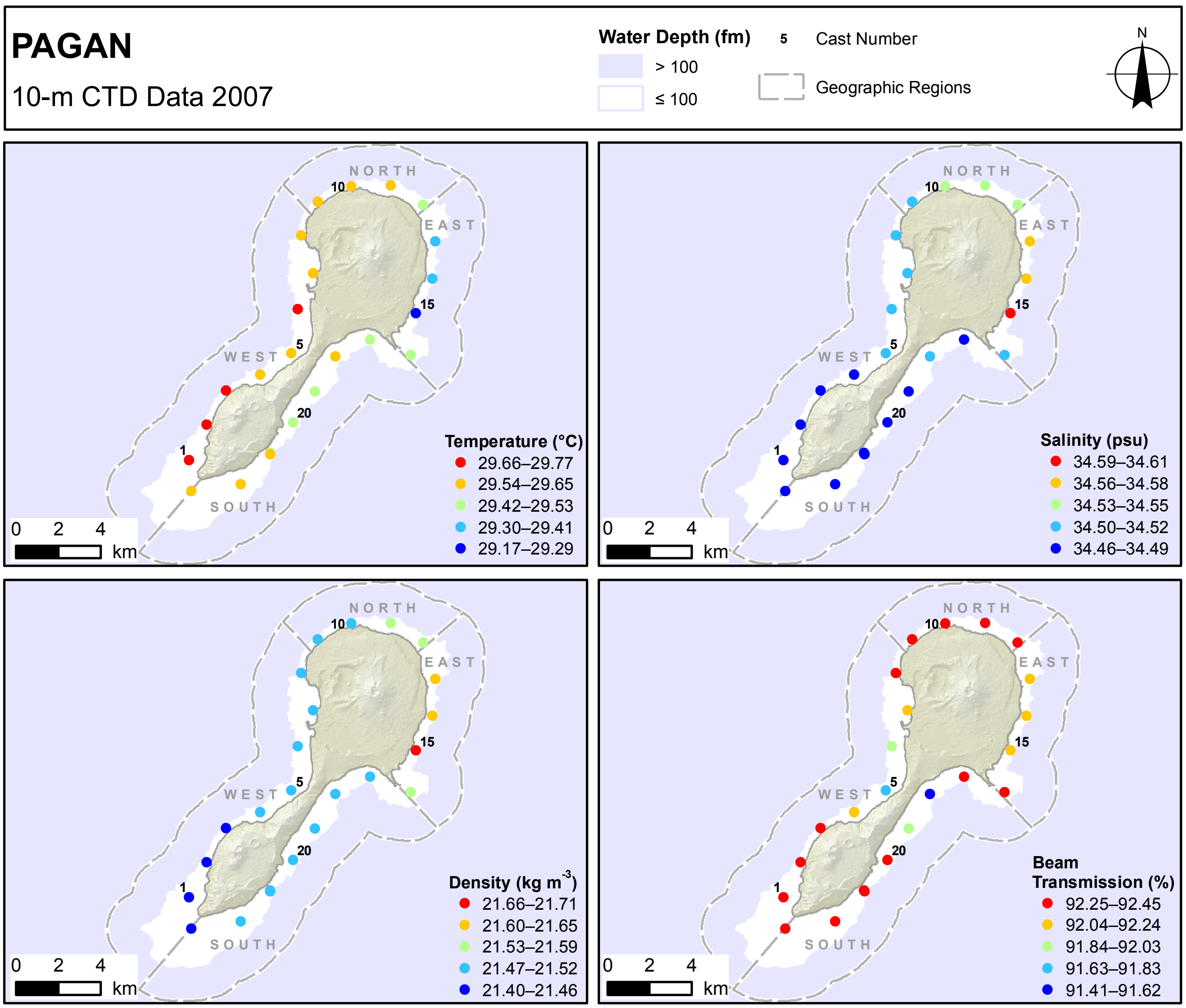


Figure 13.4.1f. Values of (*top left*) water temperature, (*top right*) salinity, (*bottom left*) density, and (*bottom right*) beam transmission at a 10-m depth from shallow-water CTD casts around Pagan on June 4–6 during MARAMP 2007.

tions of most water-quality parameters were recorded near the large bay north of Bandera Peninsula west of Mount Pagan in the west region (Fig. 13.4.1h; for place-names and their locations, see Figure 13.2a in Section 13.2: "Survey Effort"). Chl-a concentrations also were high at this location, but the highest level was observed in the south region near Apansantate. The lowest values of total nitrogen, nitrate, nitrite, and silicate all were found at the southern tip of Pagan.

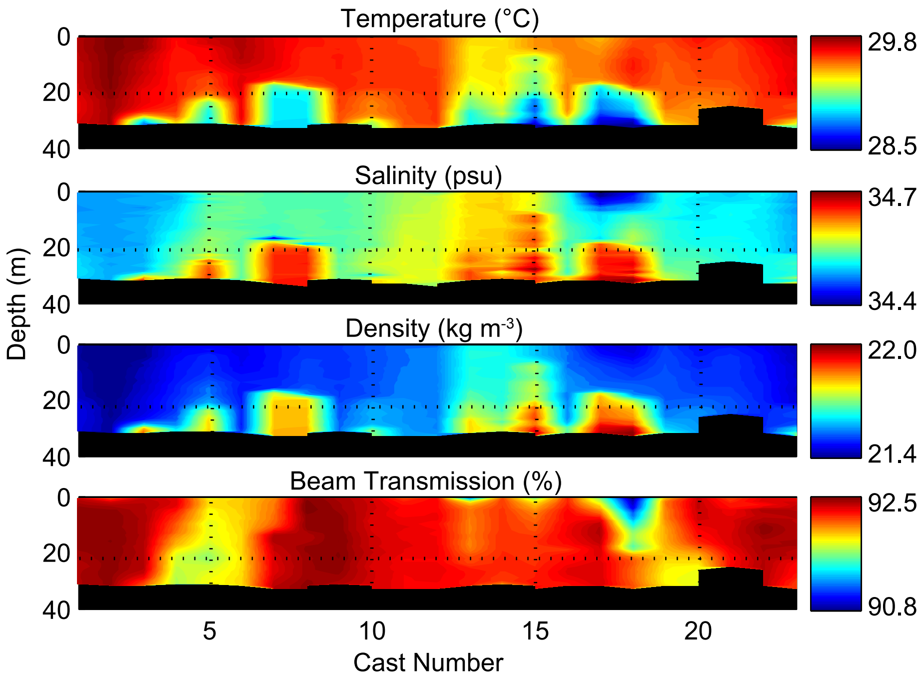


Figure 13.4.1g. Shallow-water CTD cast profiles to a 30-m depth around Pagan on June 4–6 during MARAMP 2007, including temperature (°C), salinity (psu), density (kg m^{-3}), and beam transmission (%).Profiles, shown sequentially in a left-to-right direction in this graph, correspond to cast locations that are numbered sequentially 1–23 in a clockwise direction around Pagan. For cast locations and numbers around this island in 2007, see Figure 13.4.1f.

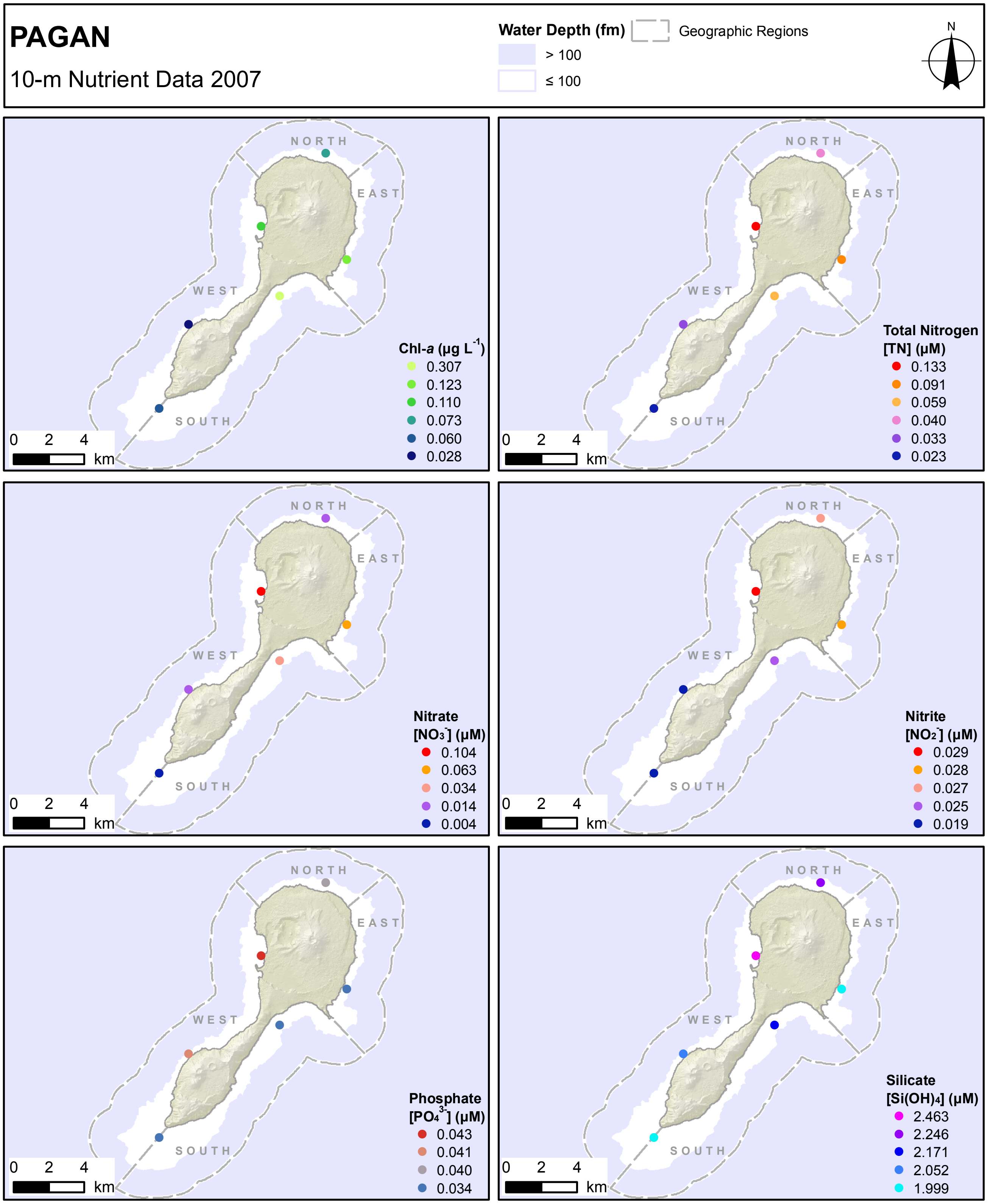


Figure 13.4.1h. Concentrations of (*top left*) Chl-*a*, (*top right*) total nitrogen, (*middle left*) nitrate, (*middle right*) nitrite, (*bottom left*) phosphate, and (*bottom right*) silicate at a 10-m depth, from water samples collected at Pagan on June 4–6 during MARAMP 2007.

Temporal Comparison

Comparisons between survey periods of shallow-water CTD data collected around Pagan during MARAMP 2003, 2005, and 2007 suggest a dynamic physical environment with few hydrographic similarities between visits. During MARAMP 2005 and 2007, temperature, salinity, and density values generally were lower along the east side of Pagan than along the west side. Beam transmission data do not show any spatial similarities between survey periods, although the maximum value did decrease with each subsequent survey as did the minimum temperature recorded. Stratification and cold-water intrusions originating from below a depth of 30 m are far more prominent in data collected in 2007 than in data from 2003 and 2005, when the water column showed increased homogeneity around this island. Data were not collected with respect to a specific tidal cycle, which could be a source of oceanographic variability. Likewise, hydrographic variation between MARAMP survey years is likely a result of differences in season. MARAMP 2007 occurred in May and June, and MARAMP 2003 and 2005 occurred in September and October. This change was made to avoid the typhoon season and reduce the probability of weather disruptions.

Water-quality data obtained during MARAMP 2005 and 2007 suggest that nutrient concentrations were variable spatially and temporally at Pagan. Spatial patterns for most measured parameters varied between these survey years, except for phosphate, which had relatively similar values in both years. The maximum silicate value was greater in 2007 (2.46 µM) than in 2005 (1.7 µM). Whether these differences resulted from a seasonal effect or some other process is unknown at this time. MARAMP 2005 occurred during a period of seasonally high precipitation, while MARAMP 2007 occurred during a period of seasonally low precipitation, likely affecting local water chemistry (for more precipitation information, see Chapter 3: "Archipelagic Comparisons," Section 3.3.1: "Seasonal Climatologies").

13.4.2 Time-series Observations

Between 2003 and 2007, two types of moored instruments were deployed at Pagan to collect time-series observations of key oceanographic parameters influencing reef conditions. The locations, depths, time frames, and other details about these deployments are provided in Figures 13.4.2a and b.

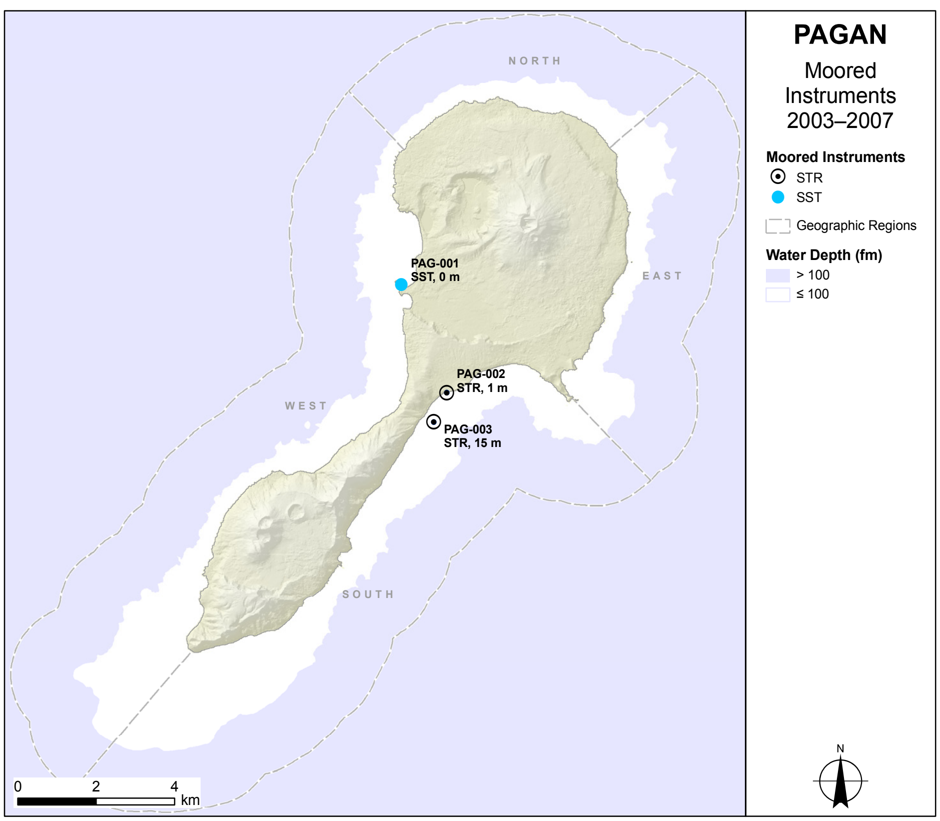


Figure 13.4.2a. Locations, depths, and types of oceanographic instrument moorings deployed at Pagan during MARAMP 2003, 2005, and 2007. Two types of instruments were moored at Pagan: sea-surface temperature (SST) buoy and subsurface temperature recorder (STR).

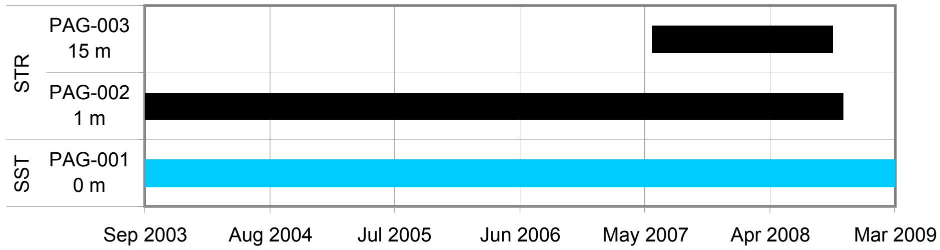


Figure 13.4.2b. Deployment timelines and depths of oceanographic instruments moored at Pagan during the period from September 2003 to March 2009. A solid bar indicates the period for which temperature data were collected by a single instrument or a series of them deployed and retrieved at a mooring site. For more information about deployments and retrievals, see Table 13.2b in Section 13.2: "Survey Effort."

Satellite-derived (Pathfinder) sea-surface temperature (SST) and in situ temperature observations suggest that the seasonal maximum for water temperatures around Pagan was usually reached in late August or September; the monthly maximum climatological mean from Pathfinder-derived SST data was 29.3°C (Fig. 13.4.2c[a]). Winter minima occurred in February with a monthly minimum climatological mean of 26.6°C. In situ SST and satellite-derived SST were relatively similar throughout this time series, with a few instances of differences of 0.1°C–0.5°C observed. SST data show that water temperatures around Pagan in August 2005 rose above the coral bleaching threshold, which is defined as 1°C above the monthly maximum climatological mean. Still, given the relatively short duration and small magnitude of this period of elevated temperature, widespread mass coral bleaching likely did not occur. It's important to note that satellite-derived SST represents the upper few millimeters of oceanographic temperatures within the region of an island, as opposed to site- or reef-specific temperatures.

Periods of elevated mean wave heights of 2–4 m were usually more frequent during winter (Fig. 13.4.2c[b]). The largest episodic events of wave heights > 4 m, however, tended to happen during periods of warm sea temperatures. Warm sea temperatures typically occurred during the period of August–December, when wave heights of > 4 m are generally associated with typhoons. This pattern was especially noticeable during the summer of 2004 with the passages of Typhoons Tingting and Chaba.

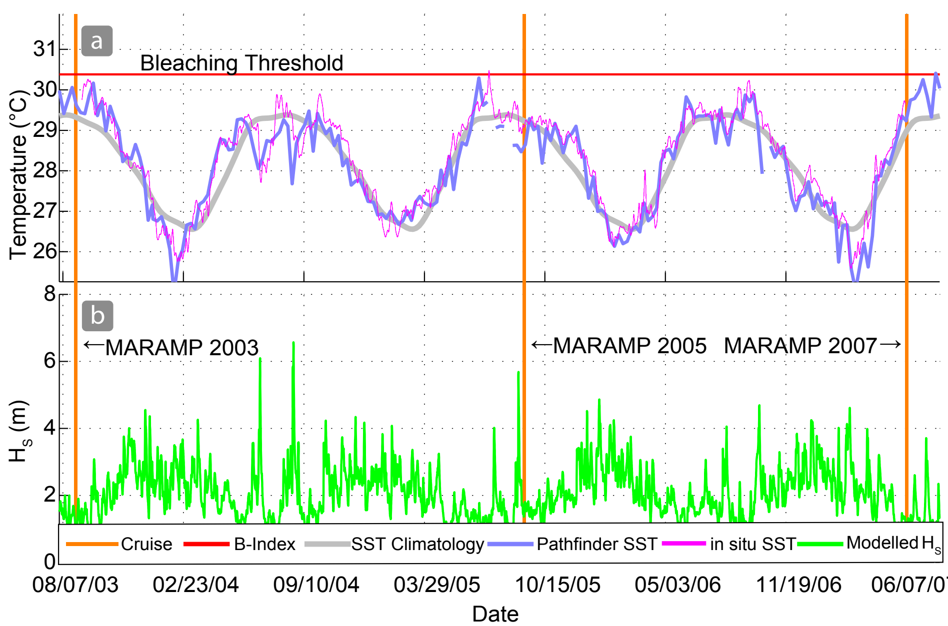


Figure 13.4.2c. Time-series observations of (*a*) SST and (*b*) wave height around Pagan for the period between August 2003 and June 2007. Remotely sensed data (SST climatology and weekly Pathfinder-derived SST) and modeled significant wave height (H_s) derived from Wave Watch III are shown with CRED in situ temperature data from SST buoys (see Fig. 13.4.2a for the buoy location). The 2 high points in the modeled wave height in the summer of 2004 show the occurrences of Typhoons Tingting and Chaba. The horizontal red and vertical orange bars represent the bleaching threshold and the MARAMP research cruise dates, respectively.

A subsurface temperature recorder (STR) mooring site was established south of Mount Pagan in 2003 at Pagan. Data from STRs deployed at this site at a depth of 1 m in the south region show a seasonal temperature variability of 4°C–6°C (Fig. 13.4.2d). Water temperatures occasionally reached maximums of ~ 32°C during the months of June–October and fell to minimums of ~ 25°C during the months of January–May. Temperature at this shallow location exceeded the coral bleaching threshold of 30.4°C each year at multiple times through the summer months of July–August. Interestingly, temperature values during the summer of 2006 were not significantly higher than values recorded in previous years, as was observed in most other temperature time series for mooring sites at other islands in the CNMI, although the period above the coral bleaching threshold may have been more extended. Diurnal temperature fluctuations of ~ 0.8°C were observed throughout this time series.

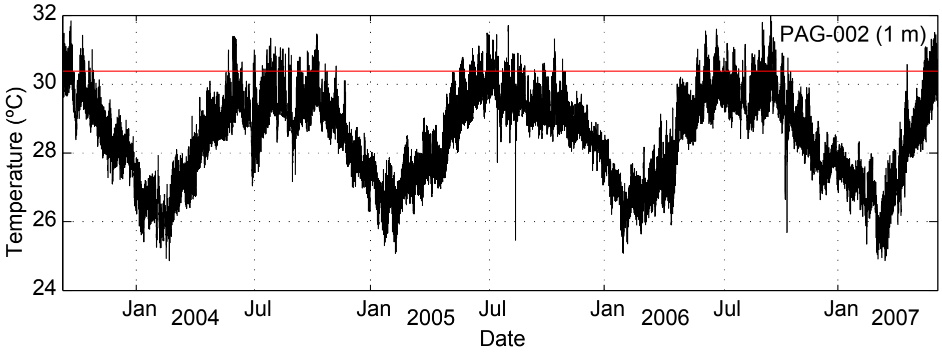


Figure 13.4.2d. Time-series observations of temperature over the period between August 2003 and June 2007 collected from 1 STR mooring site at a depth of 1 m at Pagan (see Figure 13.4.2a for the mooring location). The red line indicates the satellite-derived coral bleaching threshold, which is defined as 1°C above the maximum climatological mean.

13.4.3 Wave Watch III Climatology

Seasonal wave climatology for Pagan (Fig. 13.4.3a) was derived using the NOAA Wave Watch III model for the period of January 1997 to May 2008, and seasons were selected to elucidate waves generated by typhoons, which most frequently occur during the period of August–December (for information about the Wave Watch III model, see Chapter 2: "Methods and Operational Background," Section 2.3.7: "Satellite Remote Sensing and Ocean Modeling"). In terms of consistency, the wave regime during this period was dominated by trade wind swells characterized by frequent (> 30 d per season), short-period (8–10 s), relatively small (2–3 m) wave events originating from the east (90°). Superimposed with these short-period swells were large (> 4 m), long-period (12–16 s) wave events principally from the south (180°), although they could originate from a broad directional source (120°–200°). These large, episodic waves primarily were generated by typhoons and occurred on annual to interannual time scales. Additionally, infrequent (~ 5 d per season), long-period (12–14 s) swells with moderate wave heights (2.5–4.5 m) occurred from the west and southwest (240°–270°) and likely were associated with episodic storms. Similar to the wave regime during typhoon season, the wave climate during the period of February–June (outside the typhoon season) was also characterized by frequent (> 30 d per season) and short-period (~ 8 s) trade wind swells with relatively small wave heights (~ 2 m) originating from the east. Infrequent (< 5 d per season) and long-period (12–14 s) swells with slightly larger wave heights (~ 3 m) also occurred during this time and originated from the southwest (240°) and the northwest (330°).

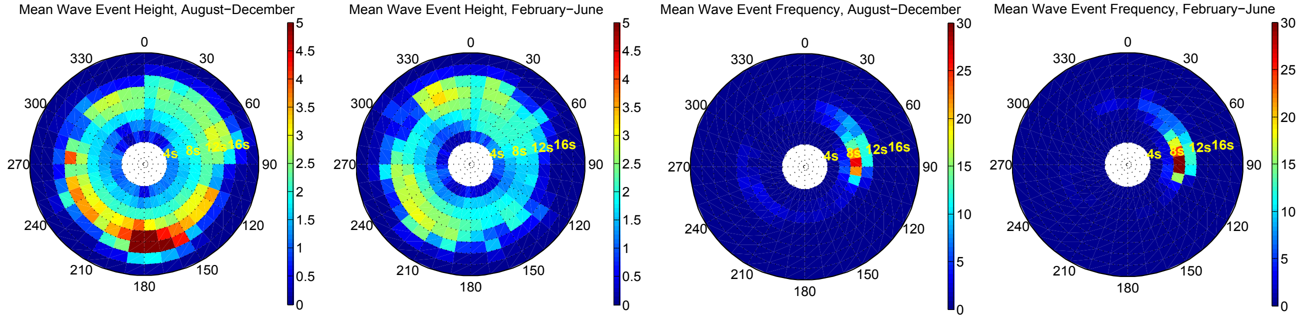


Figure 13.4.3e. NOAA Wave Watch III directional wave climatology for Pagan from January 1997 to May 2008. This climatology was created by binning (6 times daily) significant wave height, dominant period, and dominant direction from a box (1° × 1°) centered on Pagan (18° N, 145°42′ E). Mean significant wave height (*far left & left*), indicated by color scale, for all observations in each directional and frequency bin from August to December (typhoon season) and from February to June. The transition months of January and July are omitted for clarity. Mean number of days (*right & far right*) that conditions in each directional and frequency bin occurred in each season, indicated by color scale; for example, if the color indicates 30, then, on average, the condition occurred during 30 out of 150 days of that season.

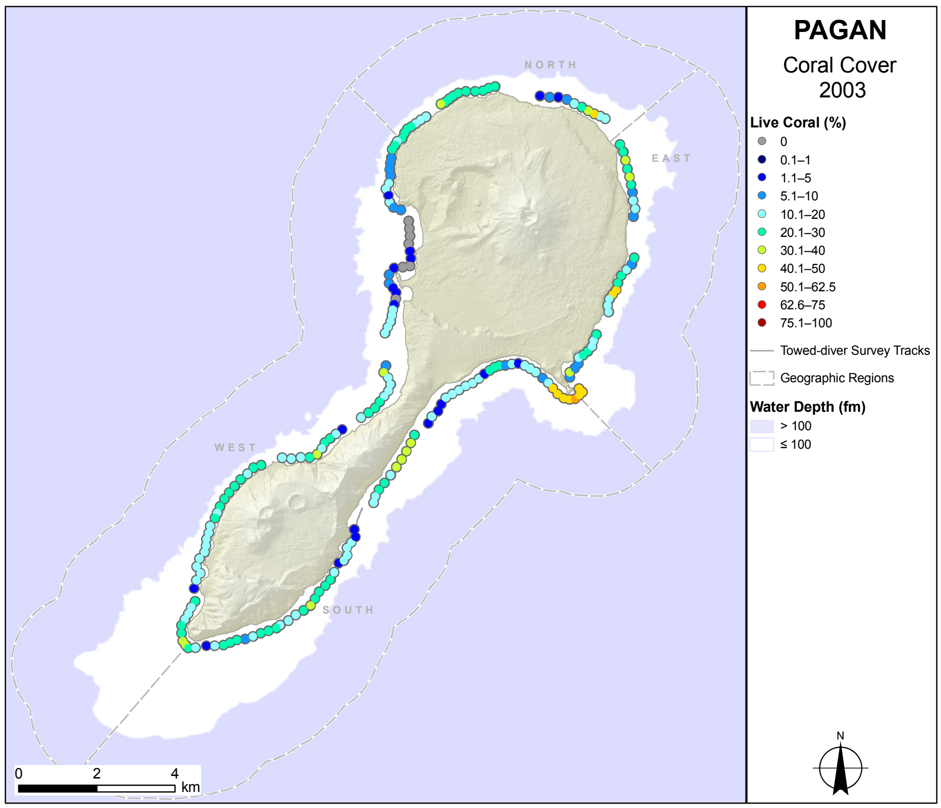
13.5 Corals and Coral Disease

13.5.1 Coral Surveys

Coral Cover and Colony Density

From MARAMP 2003 towed-diver surveys, mean cover of live hard corals on forereef habitats around the island of Pagan was 19% (SE 0.8). Coral cover was variable in all regions with the highest cover recorded near Togari Rock, in the area bordering the south and east regions, with a mean of 46% for 8 survey segments (Fig. 13.5.1a; for place-names and their locations, see Figure 13.2a in Section 13.2: "Survey Effort"). Localized areas of high coral cover also were observed north of Fuwaebosu in the south region with a mean of 35% over 4 segments. Coral cover was lowest in the west region north of Bandera Peninsula where sand was the predominant habitat.

Figure 13.5.1a. Cover (%) observations of live hard corals from towed-diver benthic surveys of forereef habitats conducted around Pagan during MARAMP 2003. Each colored point represents an estimate of live coral cover over a 5-min observation segment with a survey swath of ~ 200 × 10 m (~ 2000 m²).



During MARAMP 2003, 7 REA benthic surveys using the quadrat method on forereef habitats at Pagan documented 882 coral colonies within a total survey area of 26.25 m². Site-specific colony density ranged from 25.6 to 50.1 colonies m^{-2} with an overall sample mean of 33.6 colonies m^{-2} (SE 3.4). The highest colony density was recorded at PAG-07 in the west region, and the lowest colony density was observed at PAG-06, also in the west region (Fig. 13.5.1b).

From MARAMP 2005 towed-diver surveys, mean cover of live hard corals on forereef habitats around Pagan was 10% (SE 0.8). The highest coral cover was observed in the east region with a mean of 36% for 8 segments (Fig. 13.5.1c). A localized area of high coral cover was noted southwest of Sanmeina in the west region with a range of 50%–62.5% over a single survey segment. Coral cover was low in all other regions, compared to other areas surveyed in the Mariana Archipelago.

Towed divers during MARAMP 2005 recorded estimates of stressed-coral cover, including corals that were fully bleached (white), pale or discolored, malformed, or stricken with tumors (see Chapter 2: "Methods and Operational Background," Section 2.4.5, "Corals and Coral Disease"). Overall, 3.2% (SE 0.6) of coral cover observed on forereef habitats around Pagan appeared stressed in 2005. Occurrence of stressed-coral cover from towed-diver surveys was low for the majority of

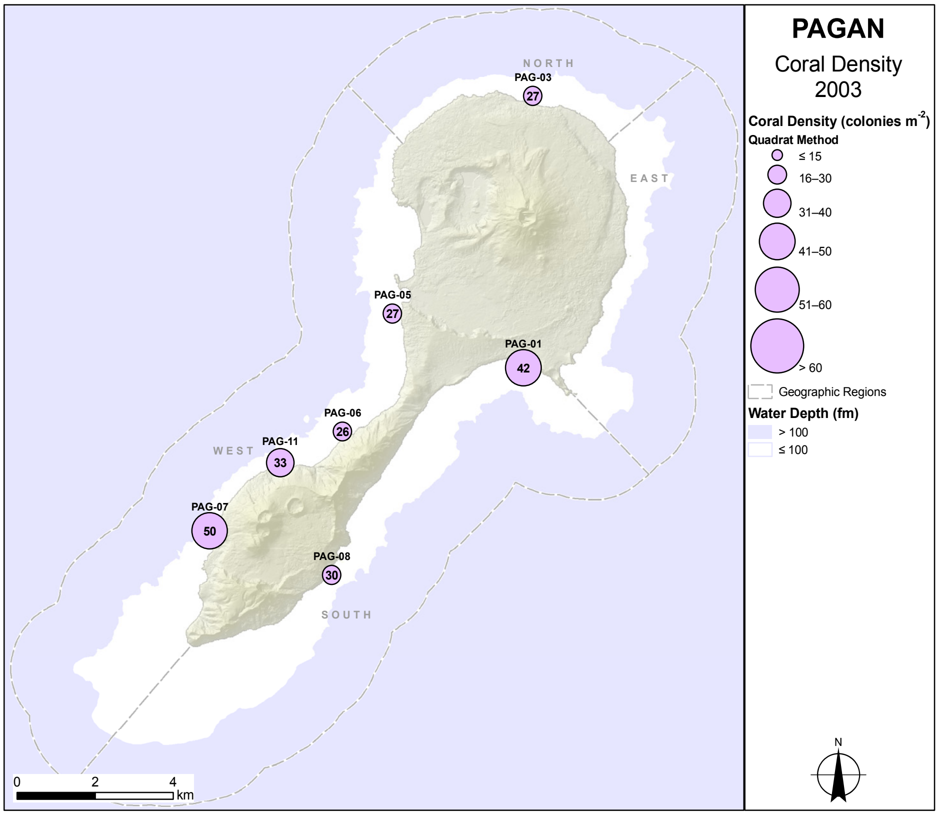


Figure 13.5.1b. Colony-density (colonies m^{-2}) observations of live hard corals from REA benthic surveys of forereef habitats conducted at Pagan during MARAMP 2003. Values are provided within each symbol. The quadrat method was used in 2003 to assess coral-colony density.

segments in the south and west regions. Relative to other areas surveyed around Pagan, high levels of stressed-coral cover were observed north of Togari Rock in the south region, around Hira Rock in the east region, and in the north region (Fig. 13.5.1c). Predation scars from crown-of-thorns seastars (*Acanthaster planci*) were noted in many areas with elevated levels of stressed-coral cover. For more about crown-of-thorns seastars (COTS) around Pagan, see Section 13.7.1: "Benthic Macroinvertebrate Surveys".

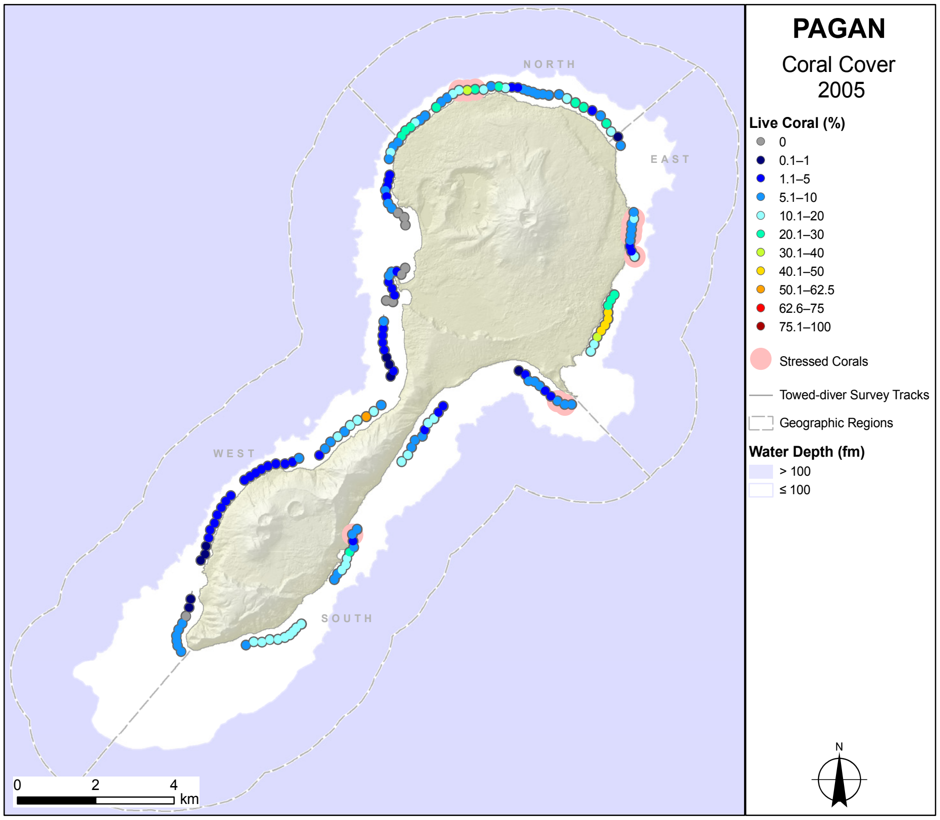
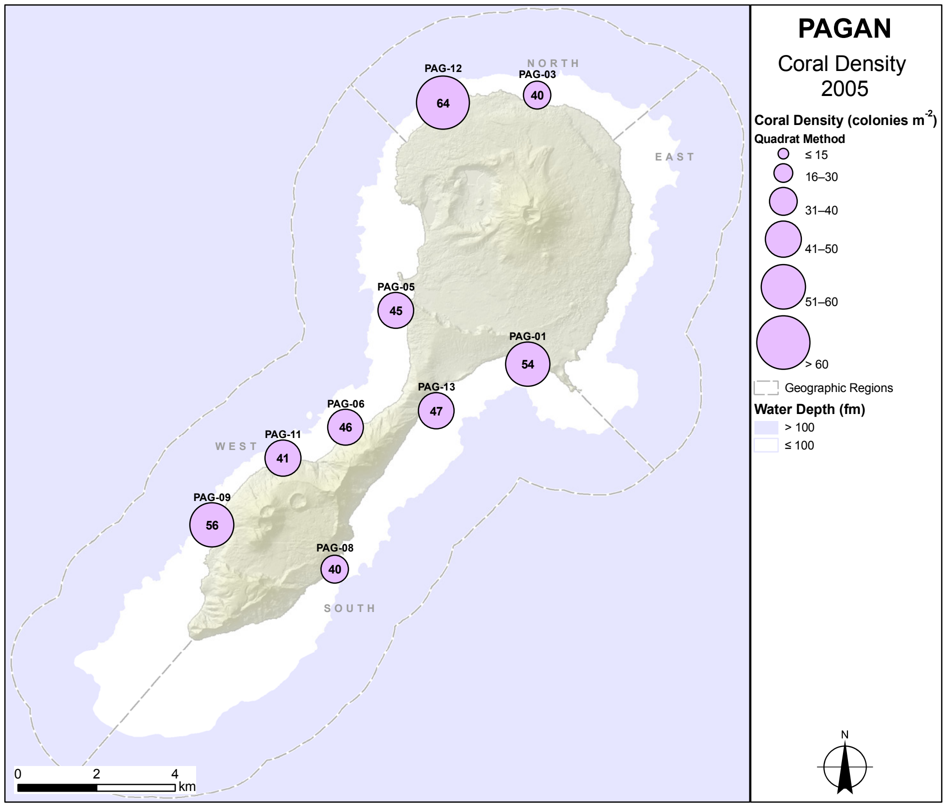


Figure 13.5.1c. Cover (%) observations of live and stressed hard corals from towed-diver benthic surveys of forereef habitats conducted around Pagan during MARAMP 2005. Each colored point represents an estimate of live coral cover over a 5-min observation segment with a survey swath of ~ 200 × 10 m (~ 2000 m^2). Pink symbols represent segments where estimates of stressed-coral cover were > 10%. Stressed-coral cover was measured as a percentage of overall coral cover in 2005.

Figure 13.5.1d. Colony-density (colonies m^{-2}) observations of live hard corals from REA benthic surveys of forereef habitats conducted at Pagan during MARAMP 2005. Values are provided within each symbol. The quadrat method was used in 2005 to assess coral-colony density.



During MARAMP 2005, 9 REA benthic surveys using the quadrat method on forereef habitats at Pagan documented 1735 coral colonies within a total survey area of 36 m^2. Site-specific colony density ranged from 39.5 to 64.3 colonies m^{-2}, with an overall sample mean of 48.2 colonies m^{-2} (SE 2.8). The highest colony density was recorded at PAG-12 in the north region, and the lowest colony density was observed at PAG-08 in the south region (Fig 13.5.1d).

From MARAMP 2007 towed-diver surveys, mean cover of live hard corals on forereef habitats around Pagan was 12% (SE 0.7). The highest coral cover was observed north of Fuwaebosu in the south region with a mean of 24% over 7 segments (Fig. 13.5.1e). A localized area of high coral cover, relative to other areas surveyed at Pagan, was recorded southwest of Sanmeina in the west region with a range of 50–62.5% over a single survey segment and large stands of *Porites rus* and *Euphyllia ancora* noted. Coral cover was low in all other regions, compared to levels observed elsewhere in the Marina Archipelago; however, despite low coral cover, large colonies of the genus *Porites* with diameters as great as 3 m were observed outside of the surveyed areas in several locations in the east and south regions.

Overall, 2% (SE 0.3) of coral cover observed on forereef habitats around Pagan appeared stressed in 2007 (see Chapter 2: “Methods and Operational Background,” Section 2.4.5, “Corals and Coral Disease”). Occurrence of stressed-coral cover, as observed in towed-diver surveys, was low for the majority of segments in the south and west regions. As in 2005, relatively high levels of stressed-coral cover were observed near Togari Rock, around Hira Rock, and in the north region (Fig. 13.5.1e). Predation scars from COTS were noted in many surveys areas with elevated levels of stressed-coral cover.

During MARAMP 2007, 9 REA benthic surveys using the line-point-intercept method were conducted on forereef habitats at Pagan. Site-specific estimates of live-hard-coral cover ranged from 3.9% to 20.6% (Fig. 13.5.1f) with an overall sample mean of 10.6% (SE 1.7). Live coral cover was highest at PAG-13 south of Apansantate in the south region and lowest at PAG-09 in the west region.

During MARAMP 2007, 9 REA benthic surveys using the quadrat method on forereef habitats at Pagan documented 1712 coral colonies within a total survey area of 36 m^2. Site-specific colony density ranged from 34.5 to 77.8 colonies m^{-2} with an overall sample mean of 47.6 colonies m^{-2} (SE 4.2). The highest colony density was recorded at PAG-12 in the north region, and the lowest colony density was observed at PAG-03 in the north region near Tarage (Fig. 13.5.1f).

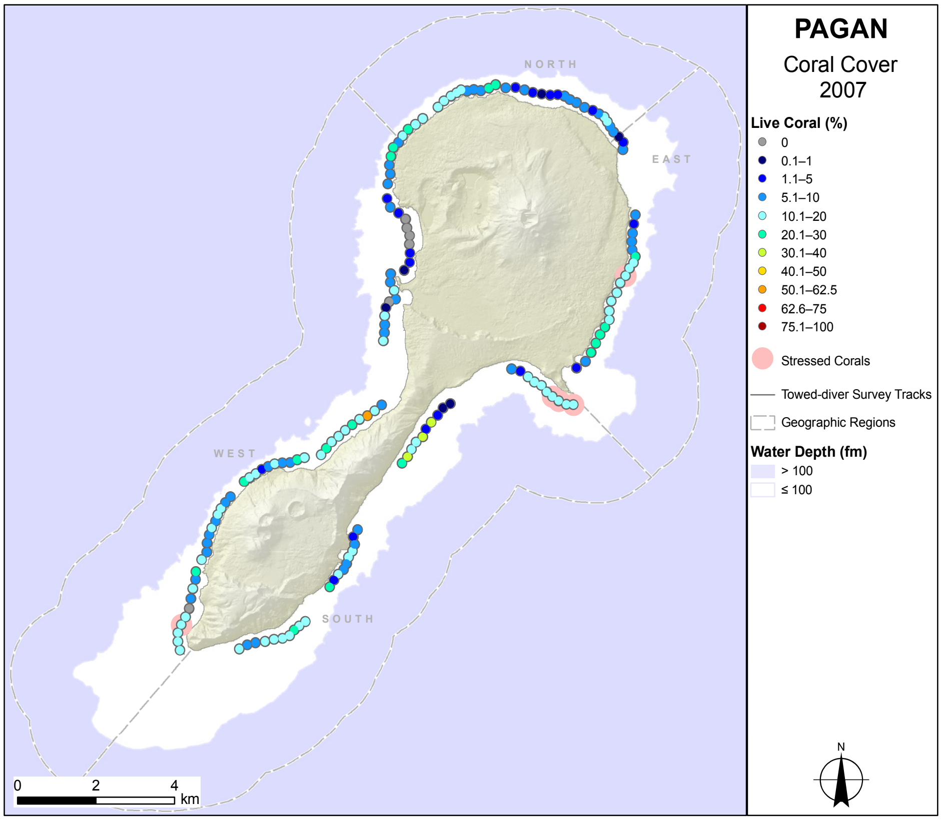


Figure 13.5.1e. Cover (%) observations of live and stressed hard corals from towed-diver benthic surveys of forereef habitats conducted at Pagan during MARAMP 2007. Each colored point represents an estimate of live coral cover over a 5-min observation segment with a survey swath of ~ 200 × 10 m (~ 2000 m^2). Pink symbols represent segments where estimates of stressed-coral cover were > 10%. Stressed-coral cover was measured as a percentage of overall coral cover in 2007.

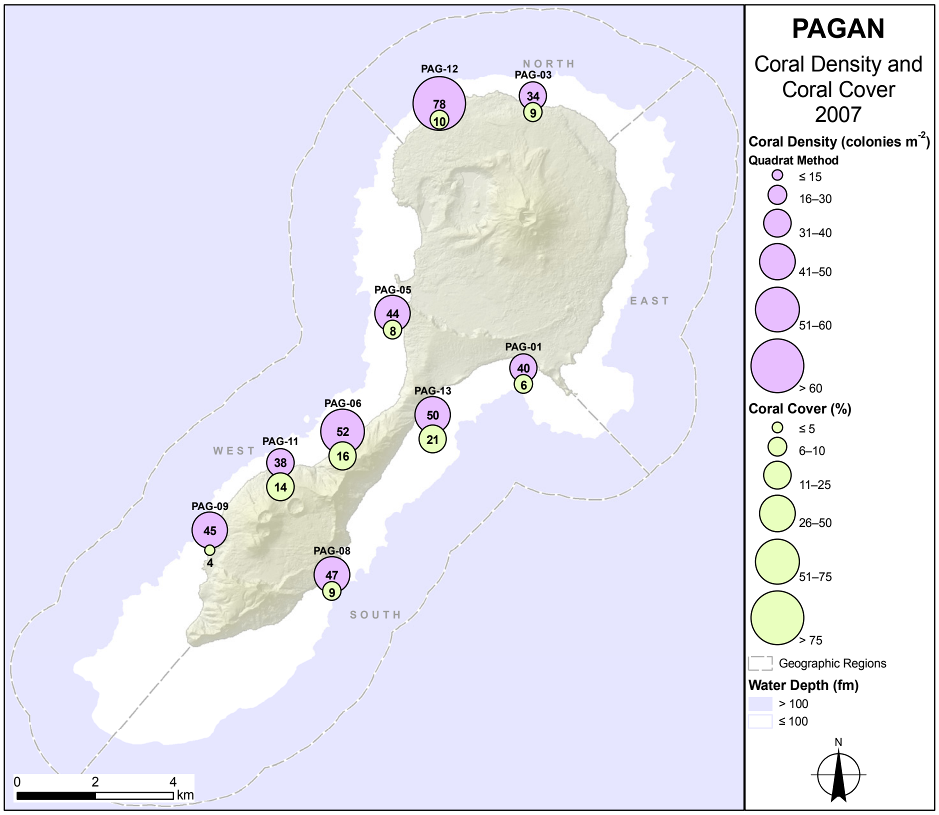


Figure 13.5.1f. Cover (%) and colony-density (colonies m^{-2}) observations of live hard corals from REA benthic surveys of forereef habitats conducted at Pagan during MARAMP 2007. Values are provided within or below each symbol. The quadrat method was used in 2007 to assess coral-colony density.

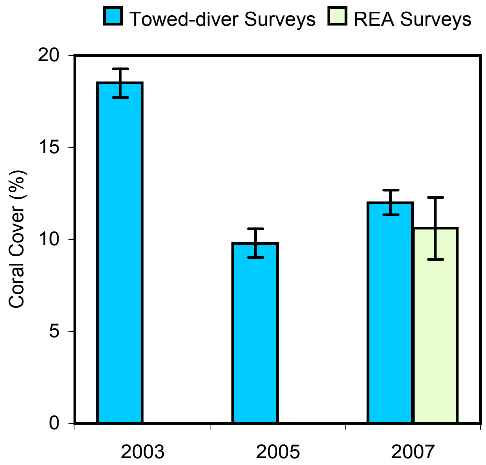


Figure 13.5.1g. Temporal comparison of mean live coral cover (%) from REA and towed-diver benthic surveys conducted on forereef habitats around Pagan during MARAMP 2003, 2005, and 2007. No REA surveys using the line-point-intercept method were conducted at Pagan in 2003 and 2005. Error bars indicate standard error (± 1 SE) of the mean.

Islandwide mean cover of live corals, estimated from towed-diver surveys of forereef habitats, varied between MARAMP survey years, ranging from 19% (SE 0.8) in 2003 to 10% (SE 0.8) in 2005 and 12% (SE 0.7) in 2007 (Fig. 13.5.1g). Coral cover in 2005 was about half the level observed in 2003. The lower cover in 2005 likely is not a reflection of spatial variation in survey effort, since the areas with the highest estimates of coral cover in 2003, most notably an area adjacent to Togari Rock bordering the south and east regions and an area north of Fuwaebosu in the south region, mostly were resurveyed in 2005. Instead, in these survey areas, along with survey areas in the east region, declines in coral cover were observed from 2003 to 2005.

COTS predation and other stressors may have contributed to the decreases in observed coral cover in these survey areas. In the south region north of Fuwaebosu, the second-greatest mean density of COTS in 2003 was recorded. In 2005, the majority of observed COTS was concentrated in the east region and in the southern half of the south region, with the third-greatest mean density of COTS recorded in the east region north of Hira Rock, where stressed-coral cover > 10% was recorded. In both 2005 and 2007, stressed-coral cover > 10% also was observed in the area adjacent to Togari Rock.

REA benthic surveys target hard-bottom communities, whereas towed-diver surveys include a wider array of substrate types. In good agreement with the overall mean from towed-diver surveys in 2007, site-specific estimates of coral cover averaged 10.6% (SE 1.7), within a range of 3.9% to 20.6%, for the 9 REA sites surveyed at Pagan in 2007 (Fig. 13.5.1g; Pagan was not surveyed for coral cover using the line-point-intercept method in 2003 or 2005).

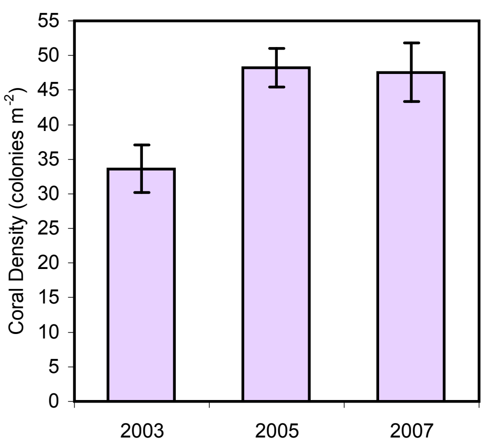


Figure 13.5.1h. Temporal comparison of mean coral-colony densities (colonies m^{-2}) from REA benthic surveys conducted on forereef habitats at Pagan during MARAMP 2003, 2005, and 2007. The quadrat method was used in all three survey years to measure coral-colony density. Error bars indicate standard error (± 1 SE) of the mean.

The quadrat method was used for REA benthic surveys conducted at Pagan during each of the 3 MARAMP survey years. Overall mean coral-colony density from REA benthic surveys of forereef habitats at 9 sites at Pagan (Fig. 13.5.1h) increased from 33.6 colonies m^{-2} (SE 3.4) in 2003 to 48.2 colonies m^{-2} (SE 2.8) in 2005; the overall sample mean in 2007 was 47.6 colonies m^{-2} (SE 4.2). A similar temporal pattern was observed at the 6 sites surveyed in all 3 survey years: PAG-01 and PAG-08 in the south region, PAG-03 in the north region, and PAG-05, PAG-06, and PAG-11 in the west region. Across these 6 sites, mean colony density was 30.9 colonies m^{-2} (SE 2.4) in 2003, 44.4 colonies m^{-2} (SE 2.3) in 2005, and 42.6 colonies m^{-2} (SE 2.7) in 2007. This rise in observed colony density between 2003 and 2005 could be a result of increased recruitment, fragmentation of existing colonies, or both.

Coral Generic Richness and Relative Abundance

Seven REA benthic surveys of forereef habitats were conducted using the quadrat method at Pagan during MARAMP 2003. At least 36 coral genera were observed at Pagan. Generic richness ranged from 11 to 17 with a mean of 14 (SE 0.9) coral genera per site (Fig. 13.5.1i). The highest generic diversity was seen at PAG-06 in the west region, and the lowest generic diversity was recorded at PAG-03 in the north region near Tarage.

Pavona, *Favia*, and *Astreopora* were the most numerically abundant genera, contributing 21%, 15.8%, and 15.6% to the total number of colonies enumerated at Pagan during MARAMP 2003. All other genera individually contributed < 10% to the total number of colonies. *Pavona* dominated the coral fauna at 3 sites in the west region: PAG-05 south of Bandera Peninsula, PAG-06, and PAG-07, contributing 33%, 24%, and 34.6% to the total number of colonies (Fig. 13.5.1i). *Favia* dominated the coral fauna at PAG-08 in the south region and PAG-03 in the north region, contributing 25.9% and 18.4% to the total number of colonies. *Astreopora* dominated at PAG-01 in the north region and PAG-11 near Pontanjaburo in the west region, contributing 34.4% and 22% to the total number of colonies.

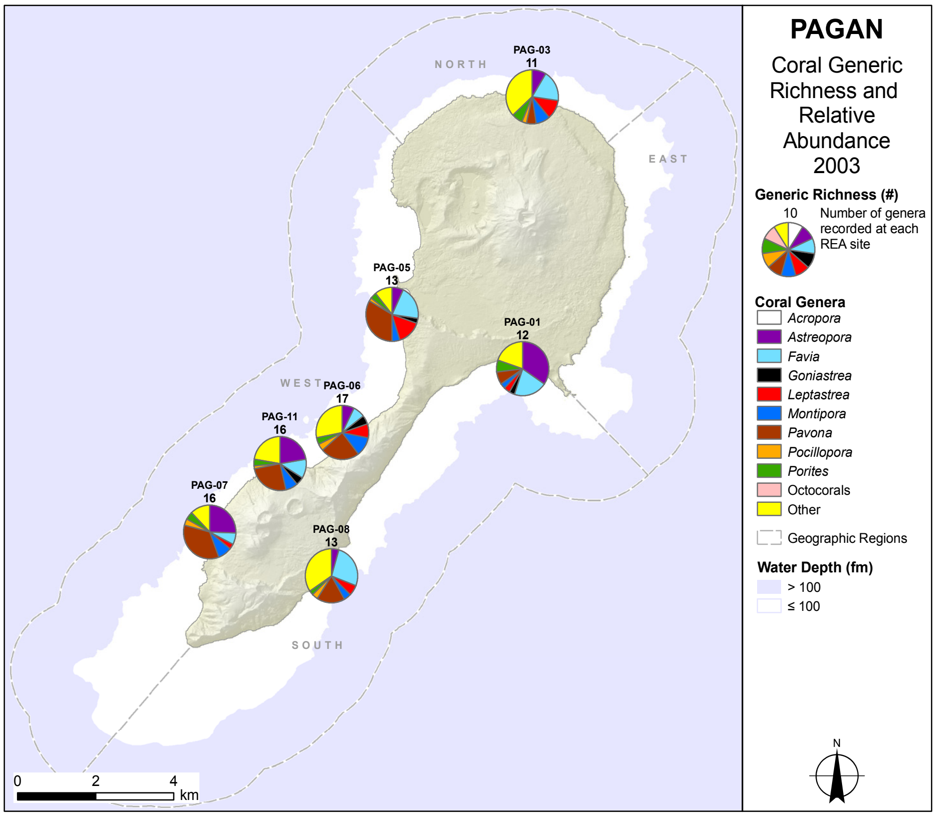


Figure 13.5.1i. Observations of coral generic richness and relative abundance of coral genera from REA benthic surveys of forereef habitats conducted at Pagan during MARAMP 2003. The pie charts indicate percentages of relative abundance of key coral genera. The quadrat method was used in 2003 to survey coral genera.

Nine REA benthic surveys of forereef habitats were conducted using the quadrat method at Pagan during MARAMP 2005. At least 28 coral genera were observed at Pagan. Generic richness ranged from 13 to 20 with a mean of 16.8 (SE 0.8) coral genera per site (Fig. 13.5.1j). The highest generic diversity was seen at PAG-13 in the south region near Apansantate, and the lowest generic diversity was recorded at PAG-08, farther south in the south region.

Favia, Pavona, and *Astreopora* were the most numerically abundant genera, contributing 20.8%, 17.9%, and 12.5% to the total number of colonies enumerated at Pagan during MARAMP 2005. All other genera individually contributed < 10% to the total number of colonies. *Pavona* dominated at PAG-06, PAG-09, and PAG-11, all in the west region, and PAG-12 in the north region (Fig. 13.5.1j), contributing 31.9%, 28.1%, 23.6%, and 27.6%, respectively, to the total number of colonies. *Favia* dominated the coral fauna at PAG-01 and PAG-08 in the south region and PAG-05 in the west region south of Shomushon, contributing 31.2%, 39.2%, and 26.7% to the total number of colonies. *Astreopora* dominated at PAG-13 in the south region, contributing 23.4% to the total number of colonies. *Pocillopora* dominated at PAG-03 in the north region near Tarage, contributing 24.4% to the total number of colonies.

Figure 13.5.1j. Observations of coral generic richness and relative abundance of coral genera from REA benthic surveys of forereef habitats conducted at Pagan during MARAMP 2005. The pie charts indicate percentages of relative abundance of key coral genera. The quadrat method was used in 2005 to survey coral genera.

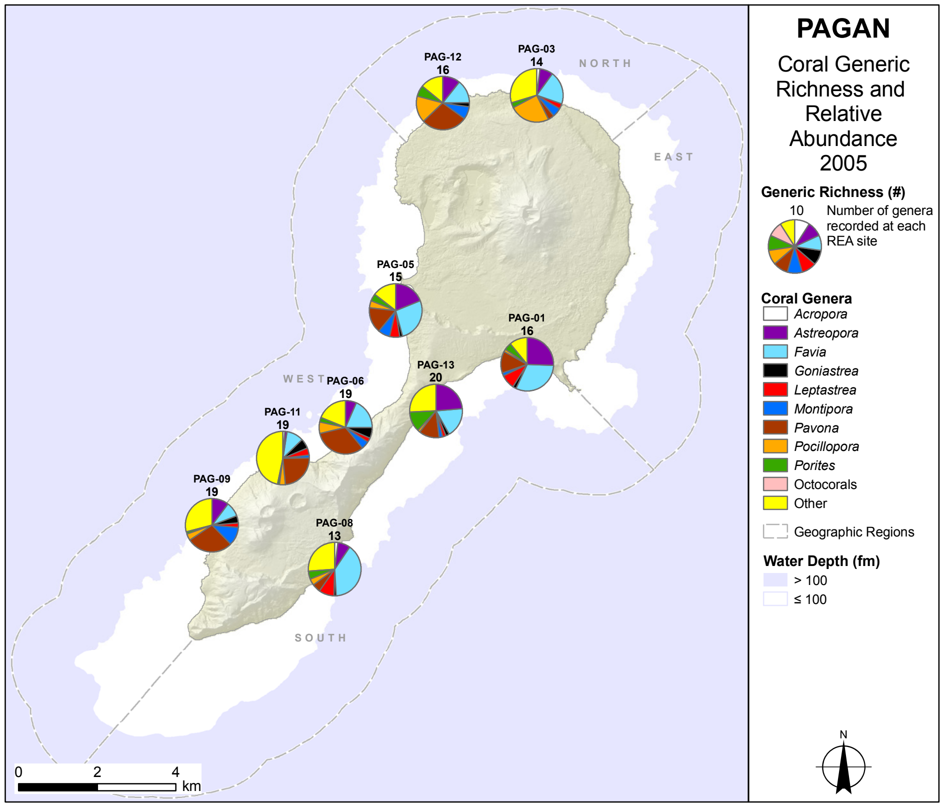
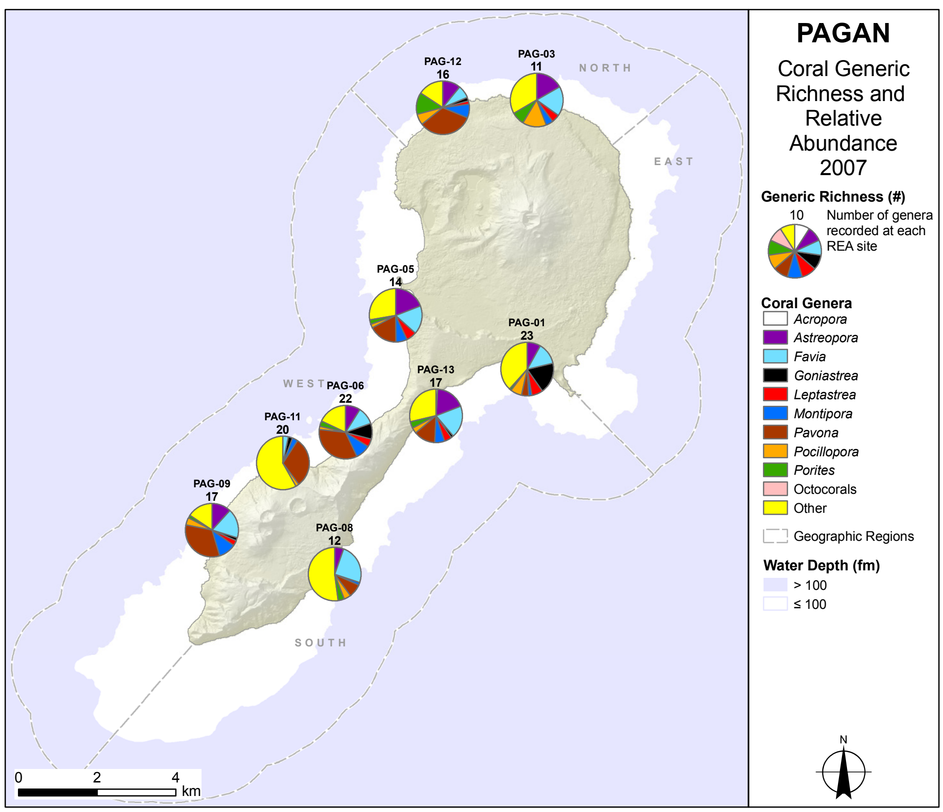


Figure 13.5.1k. Observations of coral generic richness and relative abundance of coral genera from REA benthic surveys of forereef habitats conducted at Pagan during MARAMP 2007. The pie charts indicate percentages of relative abundance of key coral genera. The quadrat method was used in 2007 to survey coral genera.



Nine REA benthic surveys of forereef habitats were conducted using the quadrat method at Pagan during MARAMP 2007. At least 30 coral genera were observed. Generic richness ranged from 11 to 23 with a mean of 16.9 (SE 1.4) coral genera per site (Fig. 13.5.1k). The highest levels of generic diversity were seen at PAG-01 and PAG-06 in the south and west regions, and the lowest generic diversity was recorded at PAG-03 near Tarage in the north region.

Pavona, Favia, and *Astreopora* were the most numerically abundant genera, contributing 19.2%, 14.7%, and 11% to the total number of colonies enumerated at Pagan during MARAMP 2007. All other genera individually contributed < 10% to the total number of colonies. As in 2005, *Pavona* dominated the coral fauna at PAG-06, PAG-09, and PAG-11, all in the west region, and PAG-12 in the north region (Fig. 13.5.1k), contributing 33.3%, 33%, 30.3%, and 33.1%, respectively, to the total number of colonies. *Favia* dominated at PAG-03 in the north region and PAG-08 and PAG-13 in the south region, contributing 18.1%, 24.6%, and 19.6% to the total number of colonies. *Astreopora* dominated at PAG-05 south of Shomushon in the west region and PAG-13 south of Apansantate in the south region, contributing 19.2% and 18.1% to the total number of colonies. *Goniastrea* dominated at PAG-01 in the south region, contributing 18.9% to the total number of colonies.

Site-specific estimates of generic richness across the 3 MARAMP survey years ranged from 11 to 23 coral genera per site on forereef habitats at Pagan. Overall mean generic-richness values (Fig. 13.5.1l) increased from 14 (SE 0.9) in 2003 to 16.8 (SE 0.8) in 2005. Generic richness in 2007 was 16.9 (SE 1.4). A similar temporal pattern was seen at the 6 sites surveyed in all 3 survey years: PAG-01 and PAG-08 in the south region, PAG-03 in the north region, and PAG-05, PAG-06, and PAG-11 in the west region. Across these 6 sites, mean generic richness increased from 13.7 (SE 0.9) in 2003 to 16 (SE 1) coral genera per site in 2005 and was 17 (SE 2.2) in 2007. This rise between 2003 and 2005 is not a result of recording additional genera at Pagan in 2005 but of recording more genera at individual sites in 2005 than in 2003.

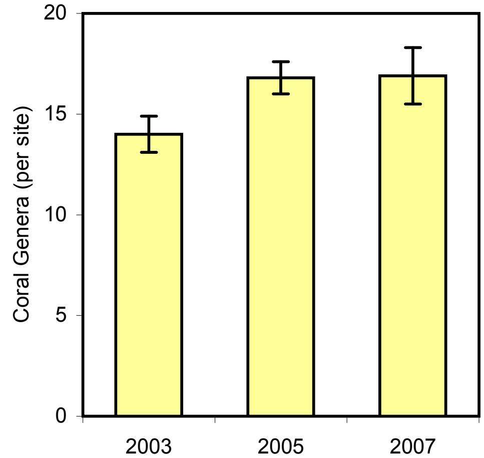


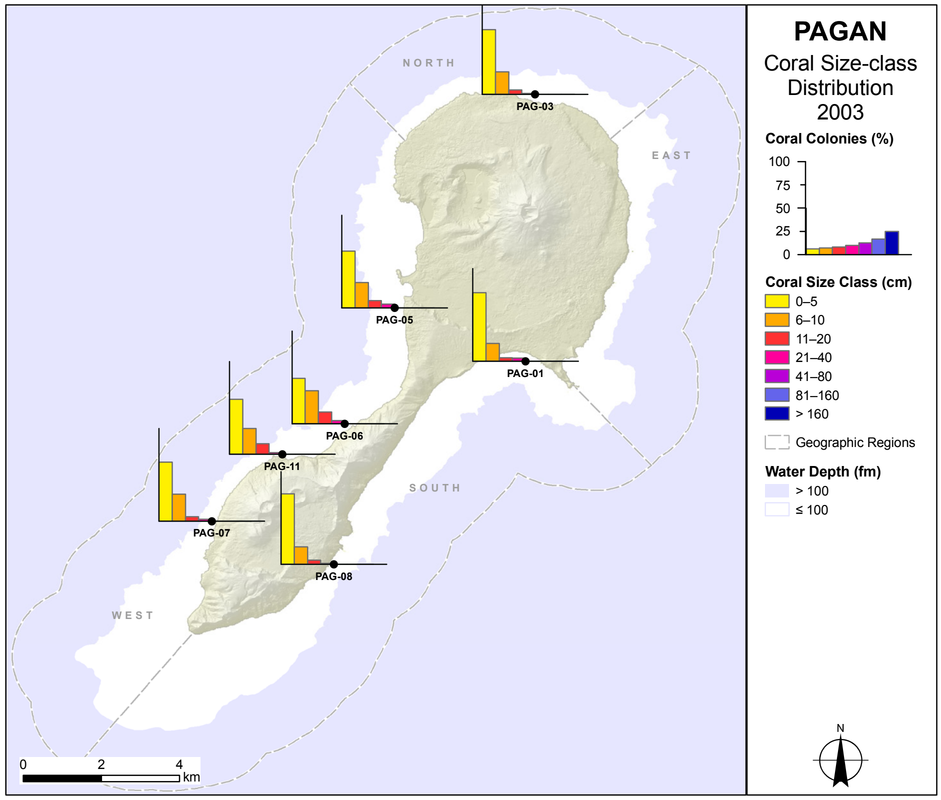
Figure 13.5.1l. Temporal comparison of overall mean numbers of coral genera per site from REA benthic surveys conducted on forereef habitats at Pagan during MARAMP 2003, 2005, and 2007. The quadrat method was used in all three survey years to survey coral genera. Error bars indicate standard error (± 1 SE) of the mean.

Across the 3 MARAMP survey years, 32 coral genera were observed on forereef habitats at Pagan. *Pavona*, *Favia*, and *Astreopora* were important components of the coral fauna, contributing > 10% to the total number of colonies enumerated in all 3 survey years. *Pavona* was the most numerically abundant taxon in 2003 and 2007 and the second-most abundant taxon in 2005, contributing 21%, 19.2%, and 17.9% to the total number of colonies enumerated in these MARAMP survey years. *Favia* was the most numerically abundant taxon in 2005 and the second-most abundant in 2003 and 2007, contributing 21%, 16.1%, and 14.8% to the total number of colonies. *Astreopora* was the third-most numerically abundant taxon in the 3 MARAMP years, contributing 15.6%, 12.5%, and 11% to the total number of colonies enumerated in 2003, 2005, and 2007. All other taxa contributed < 10% to the total number of colonies in the 3 survey years.

Coral Size-class Distribution

During MARAMP 2003, 7 REA benthic surveys of forereef habitats were conducted at Pagan using the quadrat method. The coral size-class distribution from these surveys shows that the majority (64.7%) of corals had maximum diameters ≤ 5 cm (Fig. 13.5.1m). The next 3 size classes (6–10, 11–20, and 21–40 cm) accounted for 25.9%, 7.1%, and 2.3% of colonies recorded. No colonies with maximum diameters > 40 cm were recorded. At each REA site, a majority (> 59%) of corals were in the smallest size class (≤ 5 cm), except for a site in the west region, PAG-06, where 49% of corals were in this size class.

Figure 13.5.1m. Size-class distributions of hard corals from REA benthic surveys of forereef habitats conducted at Pagan during MARAMP 2003. The observed size classes are color coded in a size-frequency chart at each REA site. The quadrat method was used in 2003 to size corals.



During MARAMP 2005, 9 REA benthic surveys of forereef habitats were conducted at Pagan using the quadrat method. The coral size-class distribution from these surveys shows that the majority (79.6%) of corals had maximum diameters ≤ 5 cm (Fig. 13.5.1n). The next 3 size classes (6–10, 11–20, and 21–40) accounted for 15.7%, 3.4%, and 1.1%, of colonies recorded, and 0.1% of corals had maximum diameters > 40 cm. At each REA site, a majority (> 72%) of corals were in the smallest size class (≤ 5 cm).

During MARAMP 2007, 9 REA benthic surveys of forereef habitats were conducted at Pagan using the quadrat method. The coral size-class distribution from these surveys shows that the majority (80.8%) of corals had maximum diameters ≤ 5 cm (Fig. 13.5.1o). The next 3 size classes (6–10, 11–20, and 21–40) accounted for 15.9%, 2.5%, and 0.7% of colonies recorded, and 0.1% of corals had maximum diameters > 40 cm. At each REA site, a majority (> 67%) of corals were in the smallest size class (≤ 5 cm).

Site-specific and overall distributions of estimated coral size classes on forereef habitats at Pagan are affected by the inherent bias in the quadrat method, which was used to census and size corals in each of the 3 MARAMP survey years. Corals whose center fell within the borders of a quadrat (50 × 50 cm) were tallied and measured in 2 planar dimensions to the nearest centimeter. Fewer large colonies than small colonies can fall within a quadrat. This bias can contribute to higher counts of colonies in the smallest size classes and lower counts of colonies in the largest size classes compared to the actual relative colony densities. At each site, 15 or 16 such quadrats were examined (total survey area = 3.75 or 4 m^2), enabling observers to closely inspect and record each coral colony within the quadrat. For more on this survey method, see Chapter 2, "Methods and Operational Background, Section 2.4.5: "Corals and Coral Disease."

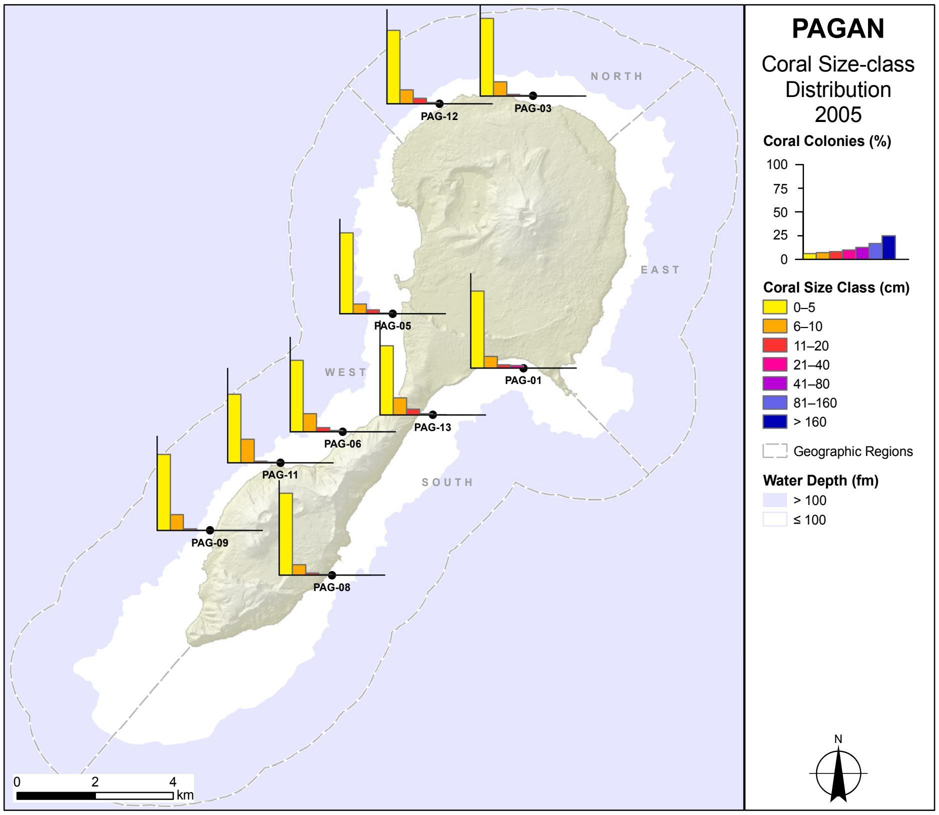


Figure 13.5.1n. Size-class distributions of hard corals from REA benthic surveys of forereef habitats conducted at Pagan during MARAMP 2005. The observed size classes are color coded in a size-frequency chart at each REA site. The quadrat method was used in 2005 to size corals.

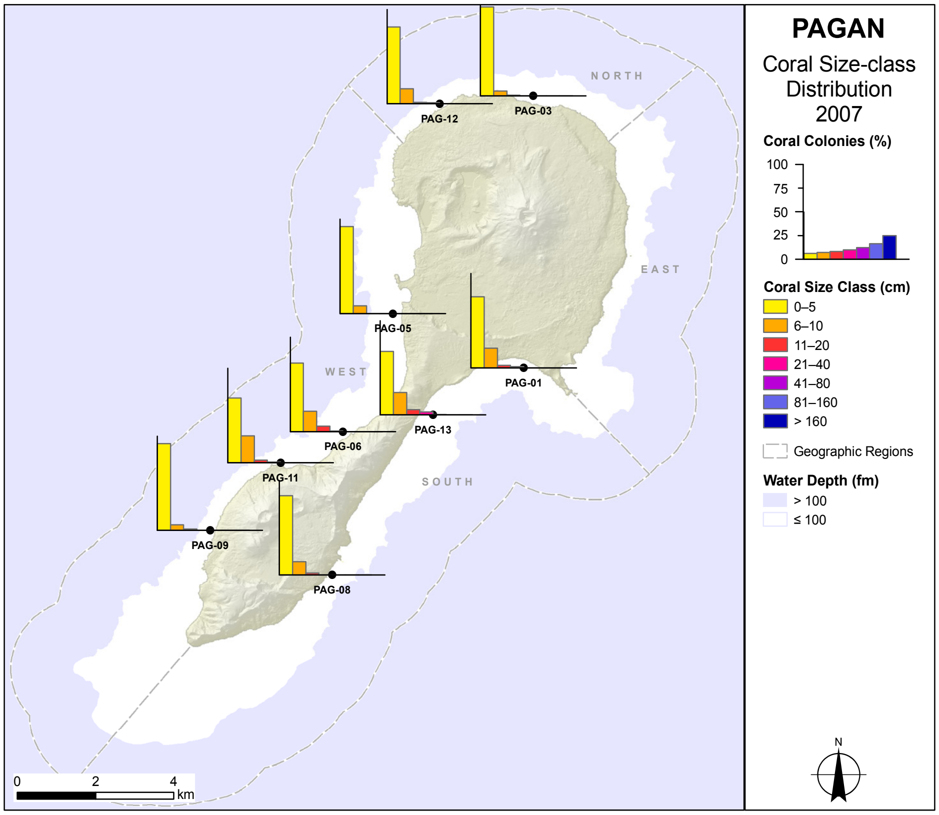
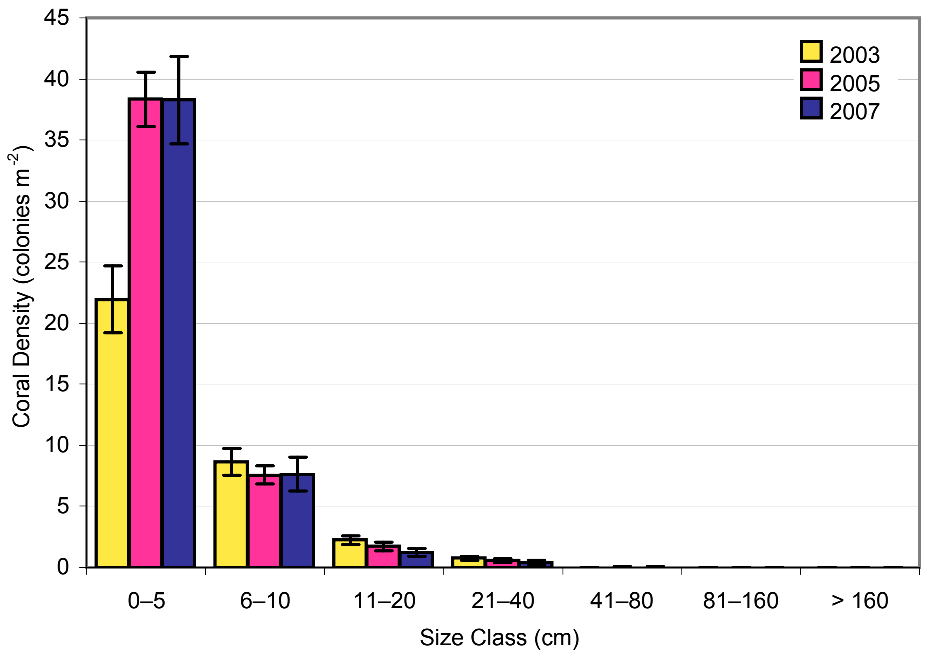


Figure 13.5.1o. Size-class distributions of hard corals from REA benthic surveys of forereef habitats conducted at Pagan during MARAMP 2007. The observed size classes are color coded in a size-frequency chart at each REA site. The quadrat method was used in 2007 to size corals.

In the 3 MARAMP survey years, the density of coral colonies was > 22 colonies m^{-2} in the smallest size class (Fig. 13.5.1p). The overall mean proportion of colonies in the smallest size class (≤ 5 cm) increased from 64.7% in 2003 to 79.6% in 2005. Similarly, the proportion of colonies in the smallest size class at each of the sites surveyed in both 2003 and 2005 (PAG-01, PAG-03, PAG-05, PAG-06, PAG-08, and PAG-11) was higher in 2005 than in 2003. The increase in coral colony density between 2003 and 2005 in the smallest size class may be a result of recruitment, fragmentation of existing colonies, or both. Minor variations in islandwide and site-specific size-class distributions between surveys in 2005 and 2007 likely are consequences of chance differences in placement of quadrats.

Figure 13.5.1p. Mean coral-colony densities (colonies m^{-2}) by size class from REA benthic surveys of forereef habitats conducted at Pagan during MARAMP 2003, 2005, and 2007. The quadrat method was used to size corals in the 3 survey years. Error bars indicate standard error (± 1 SE) of the mean.



13.5.2 Surveys for Coral Disease and Predation

During MARAMP 2007, REA benthic surveys for coral disease and predation were conducted at 9 sites on forereef habitats at Pagan, covering an area of 2700 m^2. Surveys detected 28 cases of disease, translating to an overall mean prevalence of 0.02% (SE 0.01), excluding predation. Coral-colony counts at all REA sites at Pagan were conducted using the quadrat method, resulting in higher than expected coral-colony densities and, therefore, lower disease prevalence values, relative to the levels found at sites at other islands surveyed using the belt-transect method. Two major disease conditions were observed at Pagan: fungal infections and other syndromes of unknown etiology. Fungal infections accounted for more than 90% of disease cases, and more than 95% of afflictions involving fungal infections were observed on corals of the genus *Cyphastrea*. Other disease-hosting coral genera included *Porites* and *Galaxea*. Among the 9 sites surveyed, only 3 of them contained disease: PAG-03 near Tarage in the north region, PAG-08 in the south region, and PAG-11 near Pontanjaburo in the west region. PAG-08 in the south region contained 85% of disease cases and had the greatest overall disease-prevalence value of 0.20% (Fig. 13.5.2a; the values of overall prevalence shown in this figure include predation). Prevalence values at PAG-03 in the north region near Tarage and PAG-11 in the west region near Pontanjaburo did not exceed 0.02%.

Only a few cases of coral predation attributable to COTS or corallivorous snails, such as snails from the genus *Drupella*, were observed at Pagan, particularly at PAG-12 in the north region, affecting corals of the genera *Favia*, *Goniastrea*, and *Pocillopora* and amounting to a prevalence value of 0.01%. The mean overall prevalence of predation for Pagan was 0.001% (SE 0.0005). As with fungal infections, the positive bias of the quadrat method in measuring coral density contributed to this lower overall mean prevalence value for predation at Pagan.

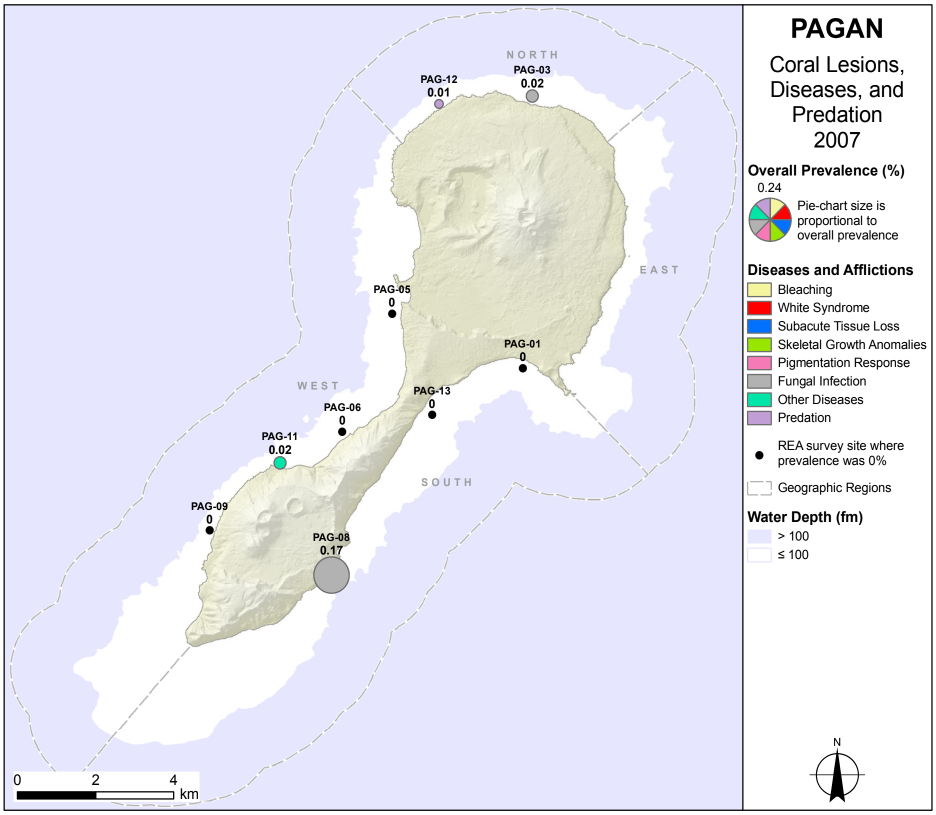


Figure 13.5.2a. Overall prevalence (%) observations of coral diseases and predation from REA benthic surveys of forereef habitats conducted at Pagan during MARAMP 2007. Prevalence was computed based on the estimated total number of coral colonies within the area surveyed for disease at each REA site. The color-coded portions of the pie charts indicate disease-specific prevalence.

13.6 Algae and Algal Disease

13.6.1 Algal Surveys

Algal Cover: Macroalgae and Turf Algae

From MARAMP 2003 towed-diver surveys, mean macroalgal cover on forereef habitats around the island of Pagan was 46% (SE 1.2). Observations of macroalgal cover in 2003 included both macroalgae and turf algae. The survey with the highest mean macroalgal cover of 64%, within a range of 30.1%–75%, occurred in the northernmost part of the west region (Fig. 13.6.1a, top left panel). Occasionally interspersed with sand flats of low complexity, habitats in this area primarily contained low-relief, spur-and-groove pavement with rock boulders and were classified as medium to high complexity. During 4 adjacent surveys in the west region, from South Point up to the coast adjacent to Maru Mountain (for place-names and their locations, see Figure 13.2a in Section 13.2: "Survey Effort"), spur-and-groove reefs exhibited higher values of macroalgal-cover than did reefs in most other survey areas around Pagan. The 2 middle surveys reported cover levels among the highest found around Pagan with means of 59% and 58%. Habitat complexity in these areas ranged from medium-low to high, and complexity values were inversely correlated with sand-cover levels. Surveys along the pavement reefs in the west and north regions, where habitat complexity ranged from medium-high to high, also recorded relatively high values of macroalgal cover with means of 55% and 54%. In contrast, the survey areas surrounding Bandera Peninsula in the west region exhibited low macroalgal cover relative to other survey areas in the rest of the west region. This area was characterized by large sand flats with small sections of reef. In the east region, the majority of surveys recorded fairly consistent values for macroalgal cover, with localized areas of high cover observed off Hira Rock and to the north of Sengao Peninsula with means of 56% and 49%, relative to other survey areas around Pagan. The habitats of these localized areas were unique among the areas surveyed in the east region, consisting of increased spur-and-groove structure with sections of bedrock and rock boulders of medium to high complexity.

TOAD surveys completed at Pagan during MARAMP 2003 were conducted at depths of 15–100 m. Analyses of TOAD video footage obtained from a survey conducted in the east region, at depths of 32–27 m, suggested that macroalgal cover was high there, with cover of 60%–100% seen in nearly half of the video frames analyzed from that survey (Fig. 13.6.1a, top left panel). Two TOAD surveys in the south region also suggested high levels of macroalgal cover: a very short survey conducted east of Pagan's isthmus at depths of 84–92 m and a survey conducted further south at depths of 30–40 m. Analyses of video footage from the remaining 4 TOAD surveys recorded little or no macroalgae.

From MARAMP 2005 towed-diver surveys, mean cover of macroalgae on forereef habitats around Pagan was 18% (SE 1.6). The survey with the highest mean macroalgal cover of 63%, within a range of 30.1%–100%, occurred west of Tarage in the north region (Fig. 13.6.1a, middle left panel) over habitat that consisted of pavement of medium-low complexity. Two surveys east of Tarage in the north region and one survey north of Hira Rock in the east region recorded greater than average macroalgal cover for survey areas around Pagan, with means of 31%, 26%, and 31%. These 3 surveys were conducted over boulder and continuous reef habitats where complexity ranged from medium-low to high. A survey in the northernmost part of the west region also reported moderate macroalgal cover, with a mean of 27%, in comparison to other areas surveyed around Pagan. Over the northern portion of this survey area, characterized as continuous reef and boulder habitat, mean macroalgal cover of 20.1%–75% was observed, whereas for the southern portion, no macroalgae were documented over habitat primarily of sand. Several other surveys recorded above average macroalgal cover, compared to other areas surveyed around Pagan, including 2 of the surveys conducted along the southeastern coast, with means of 22% and 19%, and 2 of the surveys conducted along the southwestern coast, each with a mean of 19%. The habitat observed during the 2 surveys on the southeastern coast consisted of patch reefs of medium-low to medium complexity among sand flats. The habitat seen during surveys on the southwestern coast was continuous reef with sections of rock boulders and a medium to high complexity. Large variations occurred between surveys conducted in the southern portion of the west region, where macroalgal-cover values alternated between 19% and < 4% for every other survey. This fluctuation possibly could be a result of interobserver bias as well as the presence of sandy flat terrain. It is important to note that habitat complexity and sand cover also appear to vary in the southern portion of the west region, around Sanmeina at the top of the isthmus, and Periiruu Sarahai in the southern portion of the west region. In both cases, noticeable decreases in habitat complexity and increases in sand habitat were noted (see Fig. 13.3.3a and b in Section 13.3: Benthic Mapping and Characterization"). These habitat differences also may be at least partially responsible for observed variations in macroalgal cover between towed-diver surveys. Observations of what appeared to be volcanic ash were recorded along the southwestern coast.

From MARAMP 2007 towed-diver surveys, mean cover of macroalgae on forereef habitats for Pagan was 17% (SE 1.1). The survey with the highest mean macroalgal cover of 39%, within a range of 20.1%–62.5%, occurred off Piarama in the south region (Fig. 13.6.1a, bottom left panel). The habitat in this area was continuous reef of medium complexity and dominated by species of the red algal genus *Asparagopsis*. Reports of species of the brown alga *Padina,* the green alga *Halimeda,* and cyanobacteria were also noted. Another survey in the south region, located in the vicinity of Apansantate, also recorded greater than average macroalgal cover, relative to other survey areas around Pagan, with a mean of 33%.

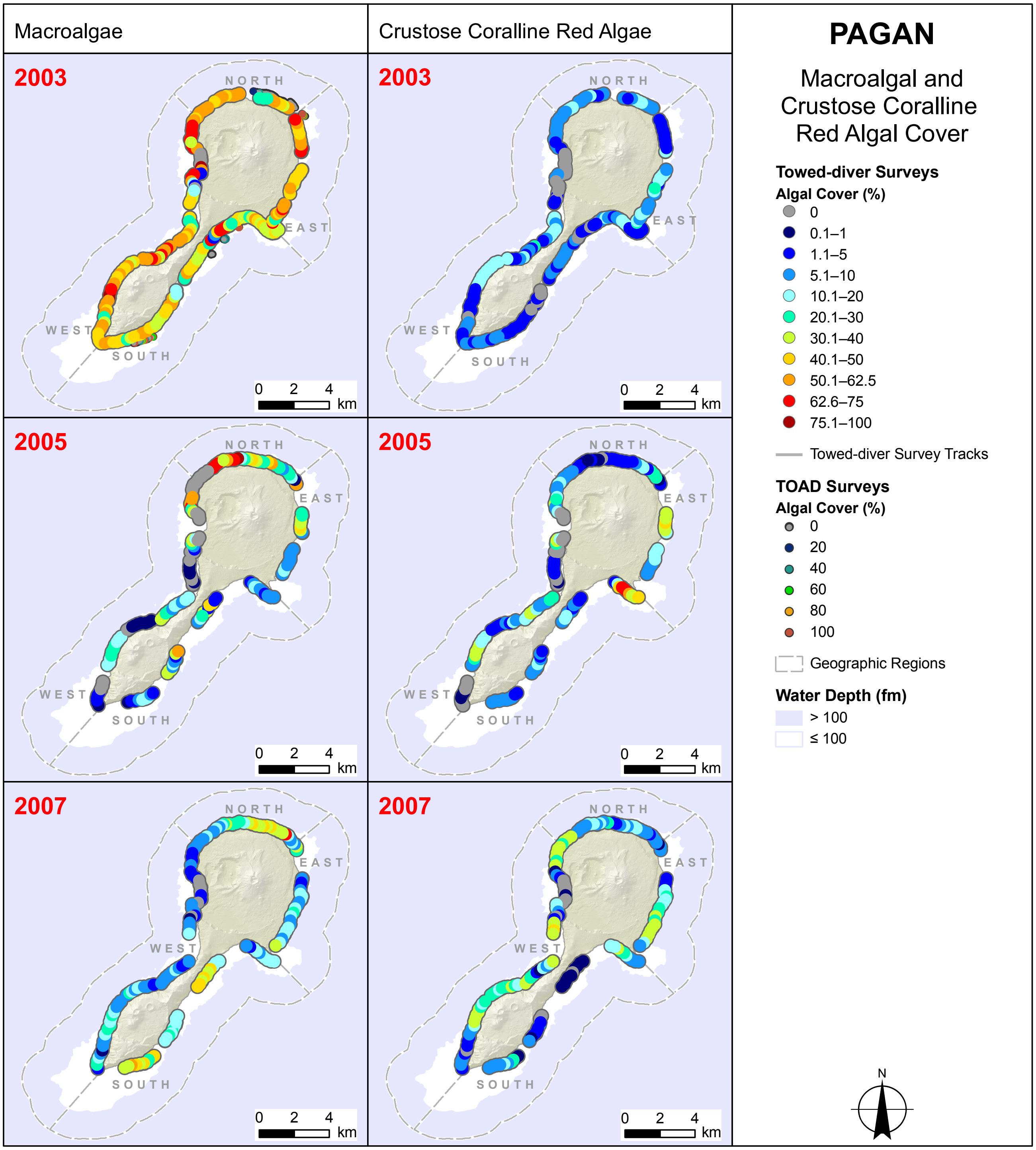


Figure 13.6.1a. Cover (%) observations for macroalgae and crustose coralline red algae from towed-diver benthic surveys of forereef habitats conducted around Pagan during MARAMP 2003, 2005, and 2007. Each large, colored point represents an estimate over a 5-min observation segments with a survey swath of ~ 200 × 10 m (~ 2000 m²). The 2003 macroalgal panel shows observations of both macroalgae and turf algae (towed-diver surveys included turf algae only during MARAMP 2003). In this panel, each small, colored point represents an estimate of algal cover from TOAD surveys.

In this survey area, a series of patch reefs and continuous reef of medium-low to medium complexity were the dominant habitat types, and taxa there consisted primarily of species of *Asparagopsis* in combination with species of *Padina*, the red alga *Liagora*, the green algae *Halimeda* and *Caulerpa*, and cyanobacteria. Three adjacent surveys conducted in the north region, moving east along continuous reef habitat of medium-low to medium-high complexity, reported elevated values of macroalgal cover, compared to most other areas surveyed at this island, with means of 20%, 36% and 24%. This habitat was dominated by species of *Asparagopsis, Padina*, the green algae *Halimeda* and *Neomeris*, and cyanobacteria. The remainder of towed-diver surveys reported low levels of macroalgal cover, with the lowest values associated with large sand flats.

During MARAMP 2007, 9 REA benthic surveys of forereef habitats at Pagan were conducted using the line-point-intercept method. Site-specific estimates of macroalgal cover ranged from 0% to 27.5% with an overall mean of 5% (SE 2.9). The survey with the highest macroalgal cover occurred in the north region at PAG-03 near Tarage (Fig. 13.6.1b). The second-highest macroalgal cover of 7.8% was observed in the south region at PAG-13 near Apansantate. For all other survey areas, macroalgal cover was < 3%, and no macroalgal cover was recorded at PAG-11 in the west region.

Turf-algal cover from these REA benthic surveys ranged from 46.1% to 80.4% with an overall mean of 67% (SE 3.8). The highest turf-algal cover was observed in the south region at PAG-08 and in the west region at PAG-05 south of Bandera Peninsula (Fig. 13.6.1b). Relative to results from other sites surveyed at Pagan, high turf-algal cover was also found at PAG-11 in the west region with 72.5%. The lowest turf-algal cover occurred at PAG-03 near Tarage in the north region.

Algal Cover: Crustose Coralline Red Algae

From MARAMP 2003 towed-diver surveys, mean cover of crustose coralline red algae on forereef habitats around Pagan was 7% (SE 0.4). The survey with the highest mean crustose-coralline-red-algal cover of 15%, within a range of 10.1%–20%, occurred southwest of Pontanjaburo in the west region (Fig. 13.6.1a, top right panel), where the habitat consisted of pavement and rock boulders of medium-high to high complexity. Just north of this area, 2 adjacent surveys recorded greater than average values of crustose-coralline-red-algal cover, relative to other survey areas around Pagan, with means of 8% and 11%. Habitats in these areas consisted of pavement with sections of continuous and spur-and-groove reef of medium-low to high complexity; areas of high complexity corresponded with the spur-and-groove areas. Additionally, the survey area to the south of Hira Rock in the east region also reported mean cover of crustose coralline red algae of 11%. The medium-complexity habitat in this area consisted of rock boulders.

From MARAMP 2005 towed-diver surveys, mean cover of crustose coralline red algae around Pagan was 12% (SE 1.1). The survey with the highest mean crustose-coralline-red-algal cover of 42%, within a range of 1.1%–75%, occurred on the reefs between Degusa and Togari Rock in the south region (Fig. 13.6.1a, middle right panel), where the habitat consisted of pavement reef of medium-low to medium-high complexity. The survey conducted to the north of Hira Rock in the east region reported mean crustose-coralline-red-algal cover of 35%. Habitat in this area was characterized as rock boulders of medium to medium-high complexity along a moderate slope. Two surveys conducted in the west region recorded greater than average values of crustose-coralline-red-algal cover, relative to other survey areas around Pagan, with means of 18% and 22%. Habitats in these areas were continuous reef with sections of rock boulders and spur-and-groove structure of predominantly medium-high complexity. Observations of what appeared to be volcanic ash were recorded on both reef areas. The remainder of towed-diver surveys reported below average levels of crustose-coralline-red-algal cover.

From MARAMP 2007 towed-diver surveys, mean cover of crustose coralline red algae around Pagan was 14% (SE 1.0). The survey with the highest mean crustose-coralline-red-algal cover of 33%, within a range of 20.1%–40%, occurred along the northwest coast of Pagan, crossing the border of the west and north regions (Fig. 13.6.1a, bottom right panel), where the habitat of medium-high to high complexity consisted of continuous reef and boulders. Almost all of the surveys conducted in the west region reported greater than average values of crustose-coralline-red-algal cover, relative to other areas surveyed around Pagan, except for the southernmost survey and the survey conducted north of Bandera Peninsula, in areas of large sand flats, where low values of crustose-coralline-red-algal cover were observed. Along the southwestern coast, mean values of crustose-coralline-red-algal cover of 24% and 26% were recorded during the survey conducted near Pontanjaburo and the adjacent survey to the south. The habitats in these survey areas consisted of continuous or irregular rocky reef of medium to medium-high complexity. Relatively low levels of crustose-coralline-red-algal cover were observed in the east region. The area between Hira Rock and Sengao Peninsula, a continuous reef habitat of medium to high complexity, exhibited the greatest cover values recorded in the east region with a mean of 28%. The adjacent survey to the south and around Sengao Peninsula reported mean crustose-coralline-red-algal cover of 15%.

During MARAMP 2007, 9 REA benthic surveys of forereef habitats at Pagan were conducted using the line-point-intercept method. Site-specific estimates of crustose-coralline-red-algal cover ranged from 0% to 11.8% with an overall mean of 4% (SE 1.5). The survey with the highest mean cover of crustose coralline red algae occurred in the west region at PAG-11 (Fig. 13.6.1b). The second-highest mean crustose-coralline-red-algal cover of 10.8% was observed at PAG-12 in the north region. No crustose coralline red algae were recorded at both PAG-08 and at PAG-13 in the south region.

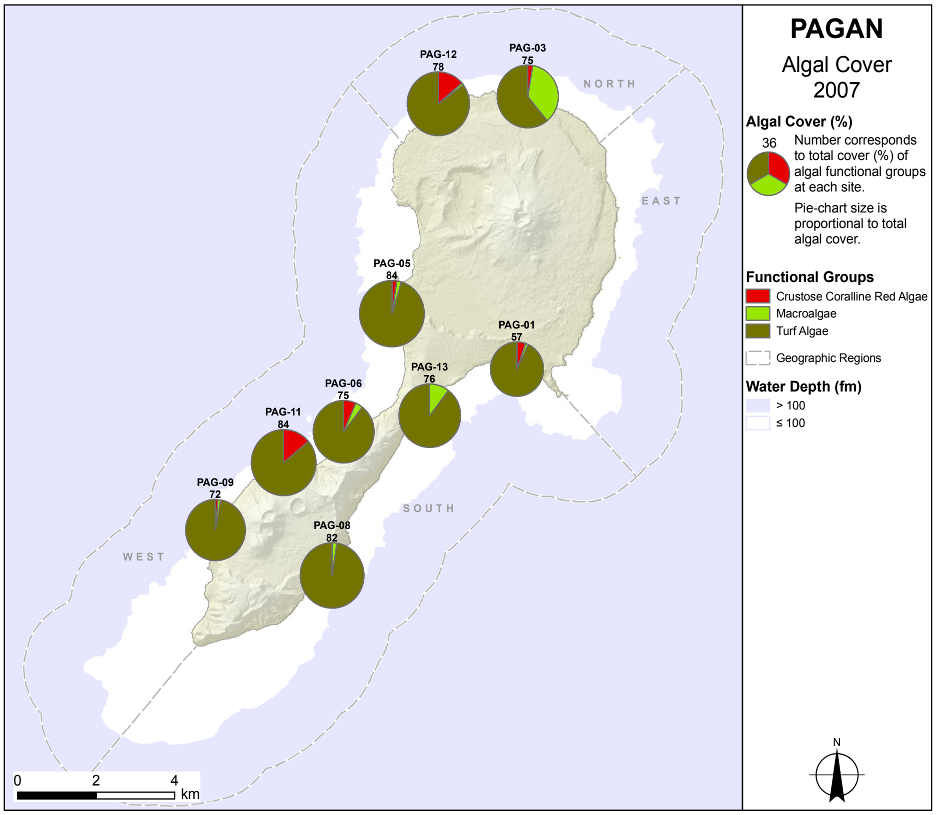


Figure 13.6.1b. Observations of algal cover (%) from REA benthic surveys of forereef habitats conducted using the line-point-intercept method at Pagan during MARAMP 2007. The pie charts indicate algal cover by functional group, and values of total cover are provided above each symbol.

Algal Cover: Temporal Comparison

Islandwide mean cover of macroalgal populations around Pagan, based on towed-diver surveys of forereef habitats, varied between MARAMP survey years by as much as 29%. In general, the greatest level of macroalgal cover was observed on reefs in the north region. The most abundant macroalgal genera in this region were *Halimeda*, *Caulerpa*, *Neomeris*, *Padina*, *Asparagopsis*, and *Liagora.* When considering survey results, keep in mind that turf algae were included, along with macroalgae, in towed-diver surveys of macroalgal cover only in 2003. Other factors, such as a change in season between survey periods, could have contributed to differences in algal cover (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys").

Overall macroalgal cover around Pagan appeared to decrease from 46% in 2003 to 18% in 2005, but this reduction in observed cover is likely a result of the change in survey method. The greatest variability between observations in these 2 survey years occurred in the west region, where mean cover values decreased from 45% to 10% across 8 surveys. Less variability was recorded in the east and south regions, although declines in observed macroalgal cover were reported in all surveys. The only increase observed from 2003 to 2005 occurred in the north region with a rise in mean macroalgal cover from 55% to 63%. From MARAMP 2005 to 2007, overall macroalgal cover essentially remained the same (Fig. 13.6.1c). The survey area with the greatest variability between 2005 and 2007 values, with a drop in mean cover from 63% to 20%, occurred in the north region west of Tarage. In addition, mean macroalgal cover values near Hira Rock in the east region decreased from 32% in 2005 to 9% in 2007. In contrast, the survey conducted near Piarama in the southernmost area of the south region reported a large increase in mean macroalgal cover from 7% to 39%.

Crustose-coralline-red-algal cover around Pagan, based on towed-diver surveys of forereef habitats, varied as much as 7% in average cover of the benthos between MARAMP survey years. Populations of crustose coralline red algae most commonly inhabited areas medium to medium-high complexity.

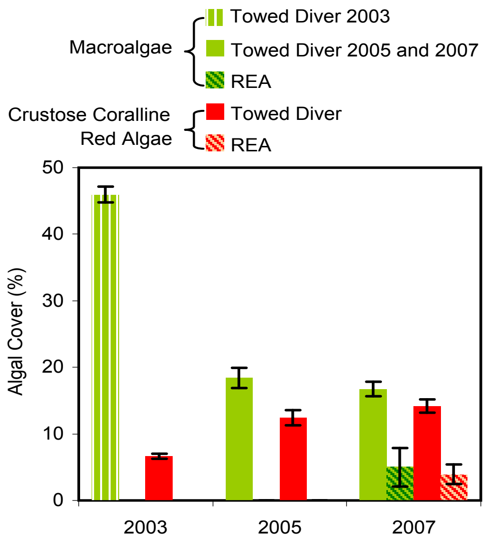


Figure 13.6.1c. Temporal comparison of algal-cover (%) valvues from surveys conducted on forereef habitats around Pagan during MARAMP 2003, 2005, and 2007. Values of macroalgal cover from towed-diver surveys include turf algae only in 2003. No REA surveys using the line-point-intercept method were conducted at Pagan in 2003 and 2005. Error bars indicate standard error (± 1 SE) of the mean.

An islandwide mean increase of 6% in observed cover of crustose coralline red algae occurred between MARAMP 2003 and 2005 (Fig. 13.6.1c). The greatest variability around Pagan between all MARAMP survey years was recorded in 3 surveys areas: near Hira Rock in the east region, along the southern coast of the Sengao Peninsula in the south region, and north of Periiruu in the west region with increases in cover values of 24%, 35%, and 20%. Between MARAMP 2005 and 2007, the greatest difference was observed in a survey area in the south region along the southern coast of Sengao Peninsula with a drop in mean cover from 42% in 2005 to 15% in 2007. In contrast, the survey area north of this peninsula reported an increase in mean crustose-coralline-red-algal cover from 11% in 2005 to 28% in 2007. For the survey area near Pontanjaburo an increase in mean cover from 5% in 2005 to 24% in 2007 was recorded, and a survey area crossing the border between the west and north regions reported an increase in cover from 9% to 33%.

Macroalgal Genera and Functional Groups

In the field, because of their small size or similarity in appearance, turf algae, crustose coralline red algae, cyanophytes (blue-green algae), and branched, nongeniculate coralline red algae are lumped into functional group categories. The generic names of macroalgae from field observations are tentative, since microscopic analysis is necessary for proper taxonomic identification. The lengthy process of laboratory-based taxonomic identification of all algal species collected at REA sites is about 90% complete for the northern islandds of the Mariana Archipelago with hundreds of species identified so far. Ultimately, based on this microscopic analysis, the generic names of macroalgae reported in this section may change and algal diversity reported for each REA site likely will increase.

During MARAMP 2003, REA benthic surveys were conducted at 8 sites on forereef habitats at Pagan. In the field, 15 macroalgal genera (5 red, 8 green, and 2 brown), containing at least 18 species, as well as 3 additional algal functional groups—turf algae, crustose coralline red algae, and cyanophytes—were observed. PAG-08, located in the south region, had the highest macroalgal generic diversity with 7 genera, containing 7 species, documented in the field. The lowest macroalgal generic diversity was found at PAG-01, located east of Degusa in the south region, with 4 species representing 4 genera recorded.

Species of the calcified red algal genus *Amphiroa* were some of the most common components of algal communities at Pagan in 2003, occurring in 47.9% of photoquadrats sampled and at all sites surveyed except PAG-03 and PAG-04 in the north and west regions (Fig. 13.6.1d). The calcified algal genus *Neomeris* was also extremely common with occurrence values of > 50% at all sites except PAG-01 in the south region and PAG-07 in the west region, where it occurred in 8.3% and 0% of sampled quadrats. The genus *Halimeda* was less common, occurring in 15.6% of all sampled photoquadrats and in 0%–83.3% of photoqudrats sampled at individual sites. Also less common was the green algal genus *Dictyosphaeria,* occurring in 0%–66.7% of sampled photoquadrats at 5 of the 8 sites surveyed at Pagan. At the genus level, most of the other 11 taxa tentatively identified occurred only at 1 or 2 sites, making distinctive spatial patterns of distribution difficult to determine for most macroalgae at Pagan.

Turf algae were exceptionally common in 2003, occurring in 82% of photoquadrats sampled at Pagan. Observed at all sites except PAG-04 in the west region, turf algal communities were found in 83.3%–100% of sampled photoquadrats (Fig. 13.6.1d). Crustose coralline red algae and cyanobacteria were less common, occurring in 31.3% and 37.5% of sampled photoquadrats.

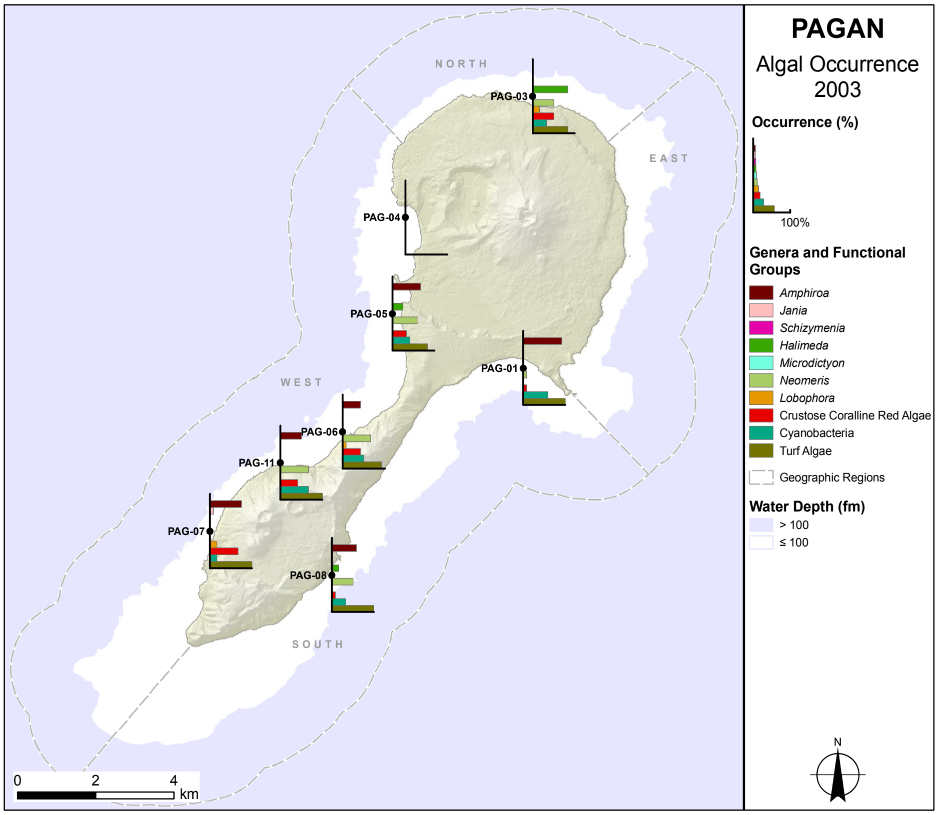


Figure 13.6.1d. Observations of occurrence (%) for select macroalgal genera and algal functional groups from REA benthic surveys of forereef habitats conducted at Pagan during MARAMP 2003. Occurrence is equivalent to the percentage of photoquadrats in which an algal genus or functional group was observed. The length of the x-axis denotes 100% occurrence.

During MARAMP 2005, REA benthic surveys were conducted at 9 sites on forereef habitats at Pagan. In the field, 21 macroalgal genera (10 red, 9 green, and 2 brown), containing at least 21 species, as well as 4 additional algal functional groups—turf algae, crustose coralline red algae, branched nongeniculate calcified red algae, and cyanophytes—were observed. PAG-13, located near Apansantate in the south region, had the highest macroalgal generic diversity with 12 genera, containing 12 species, documented in the field. The lowest macroalgal genera diversity was found in the south region at PAG-08 with 3 species representing 3 genera recorded.

Species of the genera *Amphiroa* and *Halimeda* were the dominant components of the macroalgal community at Pagan in 2005, occurring in 36.1% and 29.6% of sampled photoquadrats. Species of *Amphiroa* were found in 25%–75% of sampled photoquadrats at most sites but were absent from PAG-03 and PAG-12 in the north region and PAG-08 in the south region (Fig. 13.6.1e). Species of *Halimeda* were observed in 8.3%–100% of sampled photoquadrats at most sites but were absent from PAG-01 in the south region and PAG-06, PAG-09, and PAG-11 in the west region. No discernible spatial distributional patterns were found for either genus. At the genus level, most of the 21 taxa tentatively identified occurred only at a few sites, making distinctive spatial patterns of distribution difficult to determine for most macroalgae at Pagan. In an exception, however, the green algal species *Ventricaria ventricosa* was documented at all sites, except PAG-08 in the south region, occurring in 8.3%–33.3% of sampled photoquadrats.

Turf algae, crustose coralline red algae, and cyanobacteria were all exceptionally common in 2005, occurring in 96%, 75%, and 23% of photoquadrats sampled at Pagan. Communities of turf algae and crustose coralline red algae, ubiquitous at all sites, were found in 75%–100% and 50%–91.7% of sampled photoquadrats (Fig. 13.6.1e). Cyanobacteria were prominent components of the algal community at all sites, except PAG-03 and PAG-08 in the north and south region, occurring in 8.3%–41.7% of sampled photoquadrats. Nongeniculate coralline red algae were found only at PAG-09 in the west region, occurring in 8.3% of sampled photoquadrats.

During MARAMP 2007, REA benthic surveys were conducted at 9 sites on forereef habitats at Pagan. In the field, 30 macroalgal genera (16 red, 10 green, and 4 brown), containing at least 31 species, as well as 3 additional algal functional groups—turf algae, crustose coralline red algae, and cyanophytes—were observed. PAG-13, located near Apansantate in the south region, had the highest macroalgal generic diversity with 15 genera, containing 15 species, documented in the field. The lowest macroalgal generic diversity was also found in the south region at PAG-01, also in the south region, with 5 species representing 5 genera recorded.

Species of the red algal genera *Jania* and *Amphiroa*, the brown algal genera *Lobophora* and *Dictyota*, and the green algal genera *Neomeris* and *Halimeda* were common components of algal communities at Pagan in 2007, occurring in 76.9%, 44.4%, 47.2%, 28.7%, 37.0%, and 26.9% of sampled photoquadrats, respectively. The dominant macroalgal genus at most sites, *Jania* was found in 41.7%–91.7% of sampled photoquadrats (Fig. 13.6.1f). At the genus level, most of the 30 taxa

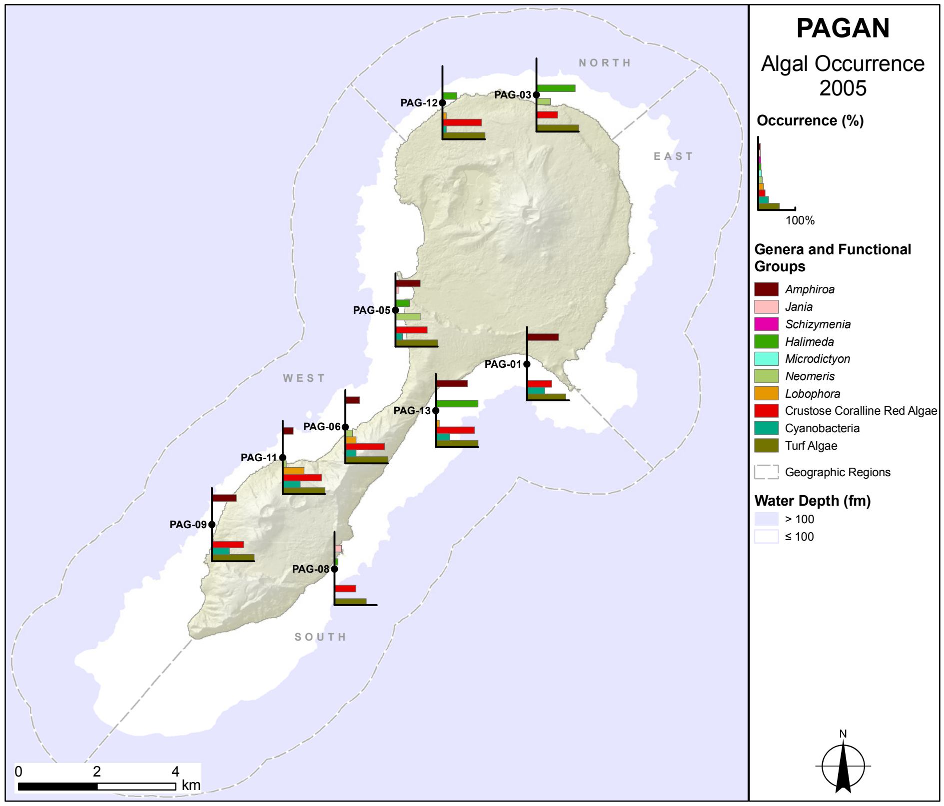


Figure 13.6.1e. Observations of occurrence (%) for select macroalgal genera and algal functional groups from REA benthic surveys of forereef habitats conducted at Pagan during MARAMP 2005. Occurrence is equivalent to the percentage of photoquadrats in which an algal genus or functional group was observed. The length of the x-axis denotes 100% occurrence.

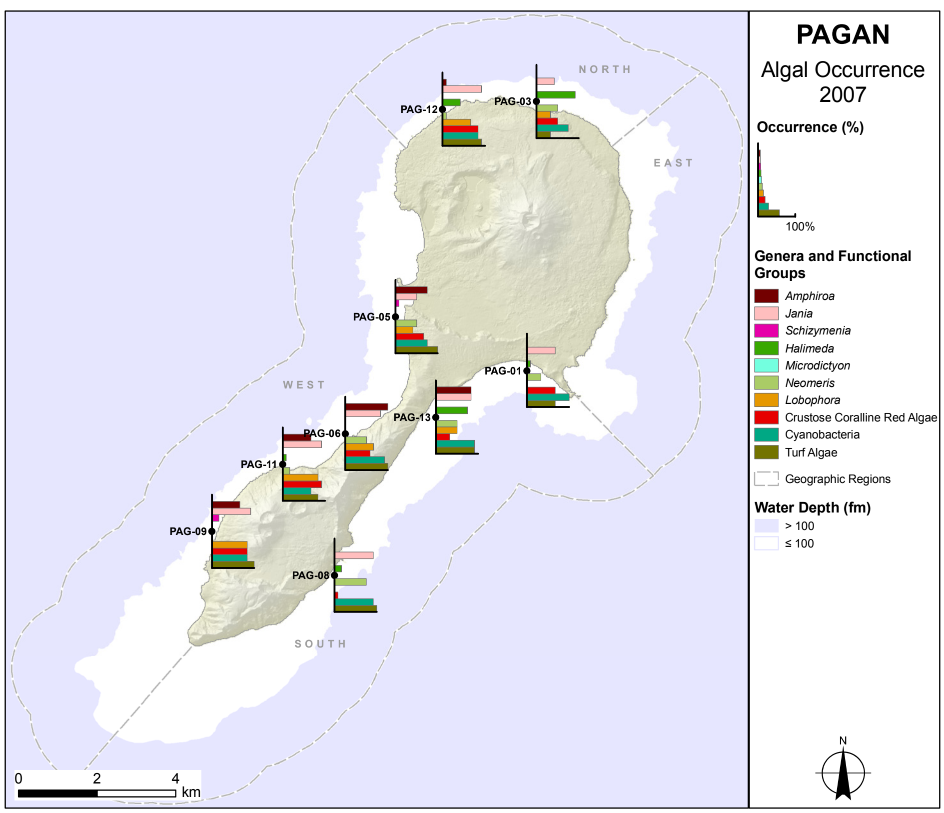


Figure 13.6.1f. Observations of occurrence (%) for select macroalgal genera and algal functional groups from REA benthic surveys of forereef habitats conducted at Pagan during MARAMP 2007. Occurrence is equivalent to the percentage of photoquadrats in which an algal genus or functional group was observed. The length of the x-axis denotes 100% occurrence.

tentatively identified occurred only at a few sites, making distinctive spatial patterns of distribution difficult to determine for most macroalgae at Pagan. However, some exceptions were found. Species of *Amphiroa* were documented at all sites in the south region except for PAG-08, occurring in 66.7%–100% of sampled photoquadrats at those sites. Species of *Halimeda* were common at several sites, occurring in 8.3%–91.7% of photoquadrats sampled at PAG-03 and PAG-12 in the north region; PAG-01, PAG-08, and PAG-13 in the south region; and PAG-11 in the west region; however, they did so without a distinct spatial pattern of distribution. Species of the calcified algal genus *Jania* were ubiquitous at all sites, and species of *Neomeris* were documented at all sites except PAG-09 in the west region. Also, species of the genus *Lobophora* occurred at all sites except PAG-01 and PAG-08 in the south region.

Turf algae, crustose coralline red algae, and cyanobacteria were all exceptionally common in 2007, occurring in 85%, 60%, and 84% of photoquadrats sampled at Pagan. Although crustose-coralline-red-algal communities were common, this functional group was observed in 8.3%–91.7% of photoquadrats sampled at the REA sites surveyed at this island (Fig. 13.6.1f). Turf algae and cyanobacteria were found in 33.3%–100% and 66.7%–100% of sampled photoquadrats.

The number of macroalgal genera recorded during MARAMP surveys conducted on forereef habitats at Pagan increased from 15 in 2003 to 21 in 2005 and 30 in 2007. Differences in survey effort and other factors likely can account for this increase in estimated macroalgal diversity (for information on data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys"). One additional site was surveyed in 2005 and 2007, compared to the number surveyed in 2003. The overall occurrence of macroalgal genera did not fluctuate greatly between the 3 MARAMP survey years. The genera *Amphiroa, Neomeris*, and *Halimeda* were consistently prominent components of the macroalgal community at Pagan during the 3 survey years, with average occurrence ranges of 36.1%–47.9%, 13%–37.5%, and 15.6%–29.6% (Fig. 13.6.1g). However, no distinct change (increasing or decreasing) in occurrence was seen for any of these genera. Species of *Jania*, *Lobophora*, and *Dictyota* steadily increased in occurrence across the 3 survey periods, and species of *Jania* and *Lobophora*, found in 76.9% and 47.2% of photoquadrats sampled in 2007, were the dominant components of the macroalgal community in 2007.

Turf algae, crustose coralline red algae, and cyanobacteria occurred in 82.3%–96.3%, 31.3%–75%, and 23.1%–84.3% of photoquadrats sampled at Pagan during MARAMP 2003, 2005, and 2007 (Fig. 13.6.1g). No clear changes in abundance of these functional groups were observed between MARAMP survey years.

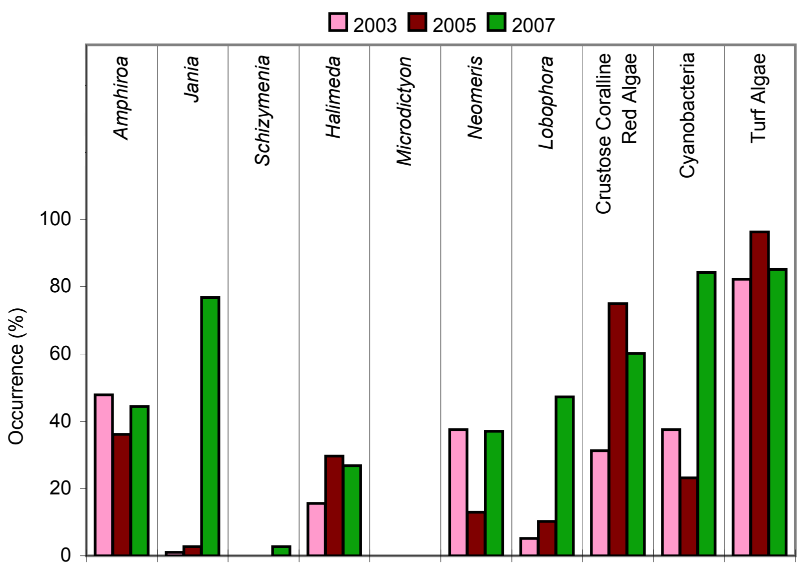


Figure 13.6.1g. Temporal comparison of occurrence (%) values from REA benthic surveys of algal genera and functional groups conducted on forereef habitats at Pagan during MARAMP 2003, 2005, and 2007.

13.6.2 Surveys for Coralline-algal Disease

During MARAMP 2007, REA benthic surveys for coralline-algal disease were conducted in concert with coral-disease assessments at 9 sites on forereef habitats at Pagan, covering a total reef area of 2700 m^2. Disease of coralline algae was found only at PAG-01, located east of Degusa in the south region. At this site, 2 cases of coralline lethal orange disease were enumerated with a density of 0.67 cases 100 m^{-2} (Fig. 13.6.2a), translating to a mean overall density of 0.07 cases 100 m^{-2}.

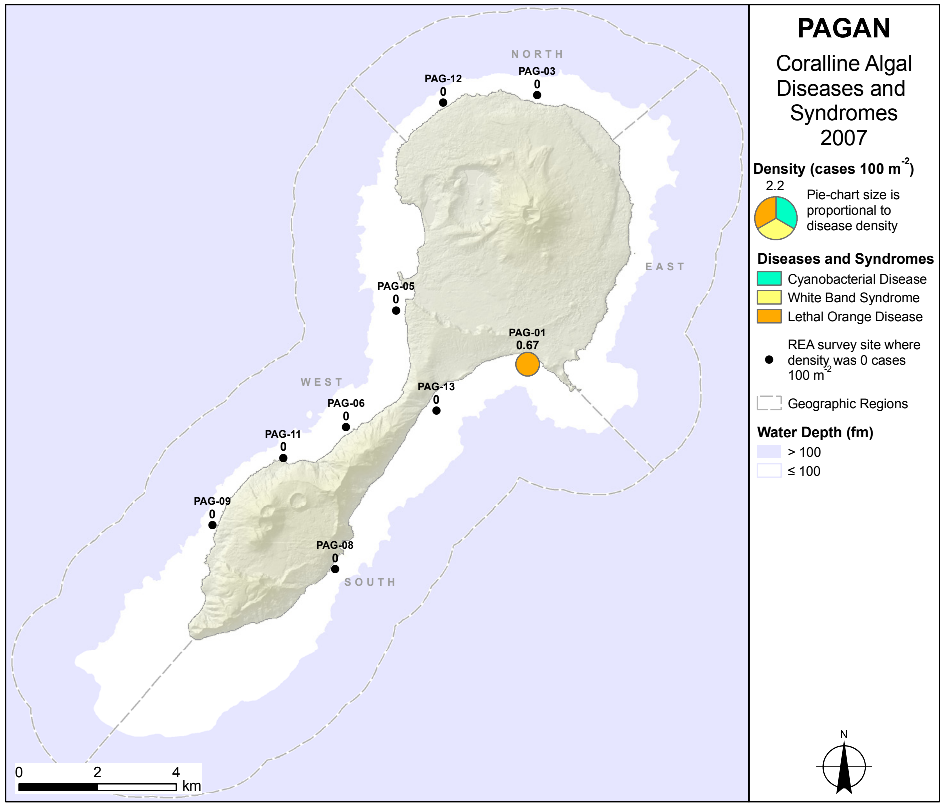


Figure 13.6.2a. Densities (cases 100 m^{-2}) of coralline-algal diseases from REA benthic surveys conducted on forereef habitats at Pagan during MARAMP 2007. The color-coded portions of the pie charts indicate disease-specific density.

13.7 Benthic Macroinvertebrates

13.7.1 Benthic Macroinvertebrates Surveys

Four groups of benthic macroinvertebrates—sea urchins, sea cucumbers, giant clams, and crown-of-thorns seastars (COTS)—were monitored on forereef habitats around the island of Pagan through REA and towed-diver benthic surveys during MARAMP 2003, 2005, and 2007. This section describes by group the results of these surveys. A list of additional taxa observed during REA invertebrate surveys is provided in Chapter 3: “Archipelagic Comparisons.”

Monitoring these 4 groups of ecologically and economically important taxa provides insight into the population distribution, community structure, and habitats of the coral reef ecosystems of the Mariana Archipelago. High densities of the corallivorous COTS can affect greatly the community structure of reef ecosystems. Giant clams are filter feeders that are sought after in the Indo-Pacific for their meat, which is considered a delicacy, and for their shells. Sea cucumbers, sand-producing detritus foragers, are harvested for food. Sea urchins are important algal grazers and bioeroders.

In 2003, 7 REA surveys and 21 towed-diver benthic surveys were conducted around Pagan. In 2005, 9 REA surveys and 17 towed-diver benthic surveys were completed. And in 2007, 8 REA surveys and 16 towed-diver benthic surveys were conducted. When considering survey results from towed-diver surveys, keep in mind that cryptic or small organisms can be difficult for divers to see, so the density values presented in this report, especially of giant clams and sea urchins, may under-represent the number of individuals present.

Overall, towed-diver surveys suggested low daytime macroinvertebrate abundance on forereef habitats around Pagan compared to the rest of the Mariana Archipelago. Minor fluctuations in observed densities between MARAMP survey periods occurred with all target groups. Temporal patterns of islandwide mean macroinvertebrate density on forereef habitats around Pagan—from towed-diver benthic surveys during MARAMP 2003, 2005, and 2007—are shown later in this section (Figs. 13.7.1d, h, l, and p).

Giant Clams

During MARAMP 2003, species of *Tridacna* giant clams were observed at all 7 REA sites surveyed and in 13 of the 21 towed-diver surveys conducted around Pagan (Fig. 13.7.1a). The overall mean density of giant clams from REA surveys was 4 organisms 100 m^{-2} (SE 1.7), and the islandwide mean density from towed-diver surveys was 0.026 organisms 100 m^{-2} (SE 0.004). Survey results suggest giant clams were most abundant at REA site PAG-01, located east of Degusa in the south region, with 13 organisms 100 m^{-2} and at PAG-05, located south of Bandera Peninsula in the west region, with a density of 7 organisms 100 m^{-2} (for place-names and their locations, see Figure 13.2a in Section 13.2: "Survey Effort"). Among all towed-diver surveys around this island, the survey completed between Degusa and Apansantate in the south region had the highest mean density of giant clams with 0.14 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.311 organisms 100 m^{-2}. The second-greatest mean density of giant clams from a towed-diver survey was 0.115 organisms 100 m^{-2}, recorded in the west region between Bandera Peninsula and Dekairu in Apaan Bay; segment densities ranged from 0 to 0.327 organisms 100 m^{-2}.

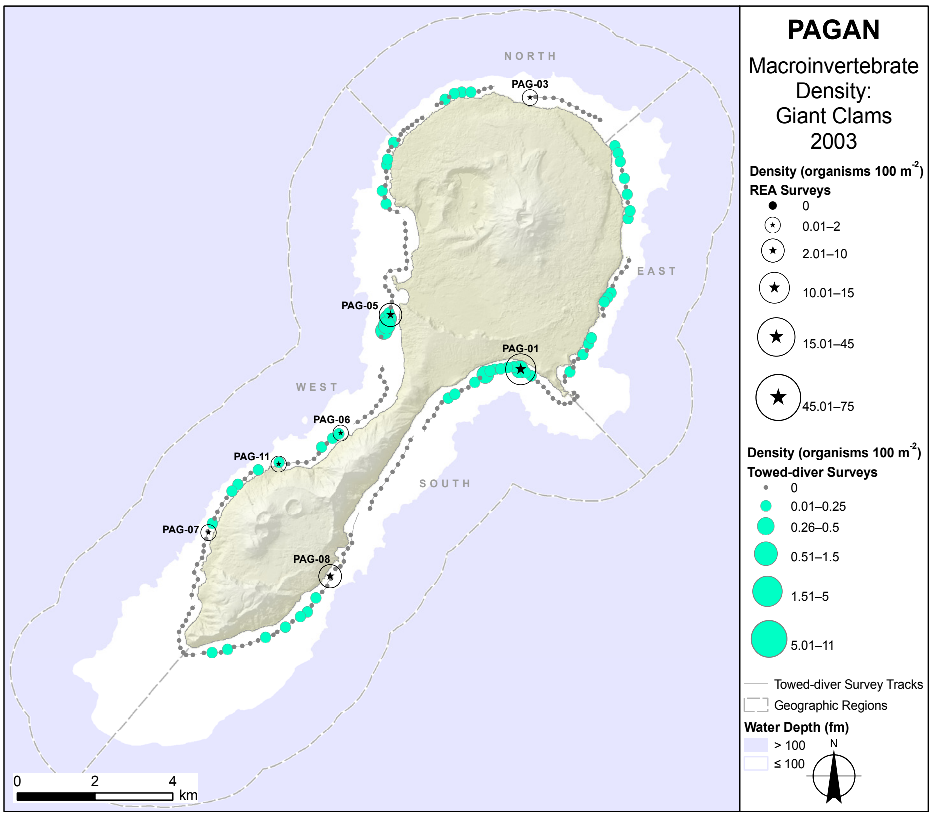
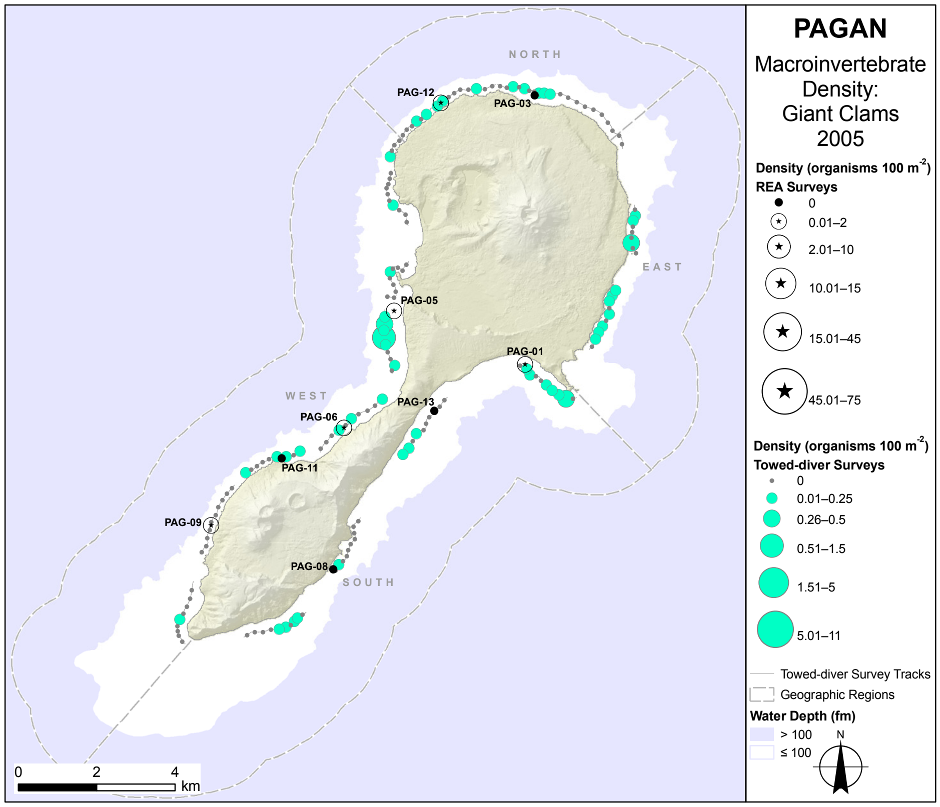


Figure 13.7.1a. Densities (organisms 100 m^{-2}) of giant clams from REA and towed-diver benthic surveys of forereef habitats conducted around Pagan during MARAMP 2003.

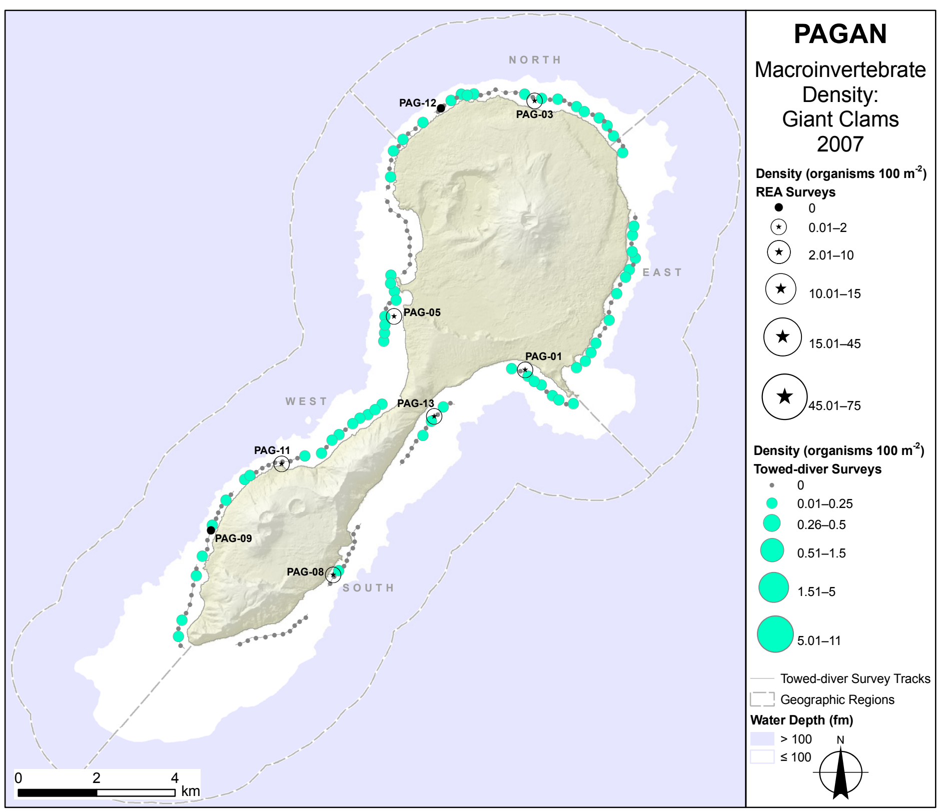
During MARAMP 2005, giant clams were observed at 5 of the 9 REA sites surveyed and in 16 of the 17 towed-diver surveys conducted around Pagan. The overall mean density of giant clams from REA surveys was 0.778 organisms 100 m^{-2} (SE 0.278), and the islandwide mean density from towed-diver surveys was 0.037 organisms 100 m^{-2} (SE 0.007). Survey results suggest that giant clams were most prevalent at PAG-01 in the south region and PAG-05 in the west region with 2 organisms 100 m^{-2} (Fig. 13.7.1b). Among all towed-diver surveys around this island, the survey completed in the west region between Bandera Peninsula and Dekairu in Apaan Bay had the highest mean density of giant clams with 0.171 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.701 organisms 100 m^{-2}. The second-greatest mean density of giant clams from a towed-diver survey was 0.093 organisms 100 m^{-2}, recorded in the east region north of Hira Rock; segment densities ranged from 0 to 0.494 organisms 100 m^{-2}.

Figure 13.7.1b. Densities (organisms 100 m^{-2}) of giant clams from REA and towed-diver benthic surveys of forereef habitats conducted around Pagan during MARAMP 2005.



During MARAMP 2007, giant clams were observed at 6 of the 8 REA sites and in 14 of the 16 towed-diver benthic surveys conducted around Pagan. The overall mean density of giant clams from REA survey was 0.542 organisms 100 m^{-2} (SE 0.17), and the islandwide mean density from towed-diver surveys was 0.033 organisms 100 m^{-2} (SE 0.004).

Figure 13.7.1c. Densities (organisms 100 m^{-2}) of giant clams from REA and towed-diver benthic surveys of forereef habitats conducted around Pagan during MARAMP 2007.



Survey results suggest giant clams were most abundant at PAG-13 near Apansantate in the south region with 1.333 organisms 100 m^{-2} (Fig. 13.7.1c). Among all towed-diver surveys around this island, the survey completed between Togari Rock and Degusa in the south region had the highest mean density of giant clams with 0.079 organisms 100 m^{-2}; segment densities for this survey ranged from 0 to 0.213 organisms 100 m^{-2}. The second-greatest mean density of giant clams from a towed-diver survey was 0.075 organisms 100 m^{-2}, recorded in the west region between Bandera Peninsula and Dekairu; segment densities ranged from 0 and 0.241 organisms 100 m^{-2}.

Towed-diver surveys suggested low abundance of giant clam around Pagan during the 3 MARAMP survey periods, relative to the rest of the Mariana Archipelago (Fig. 13.7.1d). Minor fluctuations in densities were observed, but this variation is not necessarily indicative of changes in the population structure of giant clams (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys").

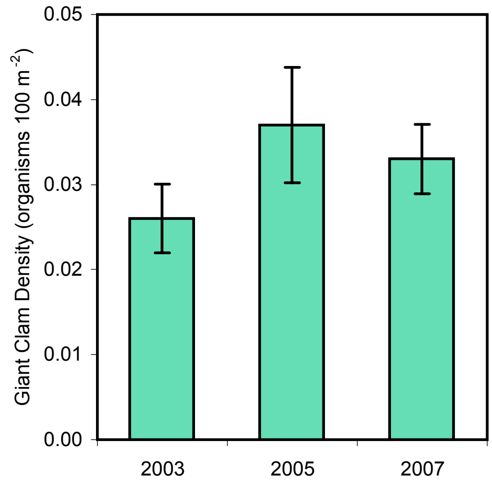


Figure 13.7.1d. Temporal comparison of mean densities (organisms m^{-2}) of giant clam from towed-diver benthic surveys conducted on forereef habitats around Pagan during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Crown-of-thorns Seastars

During MARAMP 2003, crown-of-thorns seastars (*Acanthaster planci*) were observed at 1 of the 7 REA sites surveyed and in 5 of the 21 towed-diver surveys conducted around Pagan. PAG-06 in the west region had 1 organism 100 m^{-2}. The islandwide mean density of COTS from towed-diver surveys was 0.002 organisms 100 m^{-2} (SE 0.001). Among all towed-diver surveys around this island, the survey completed in the north region had the highest mean density of COTS with 0.016 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.119 organisms 100 m^{-2} (Fig. 13.7.1e). The second-greatest mean density of COTS from a towed-diver survey was 0.010 organisms 100 m^{-2}, recorded just north of Fuwaebosu in the south region; segment densities ranged from 0 to 0.061 organisms 100 m^{-2}.

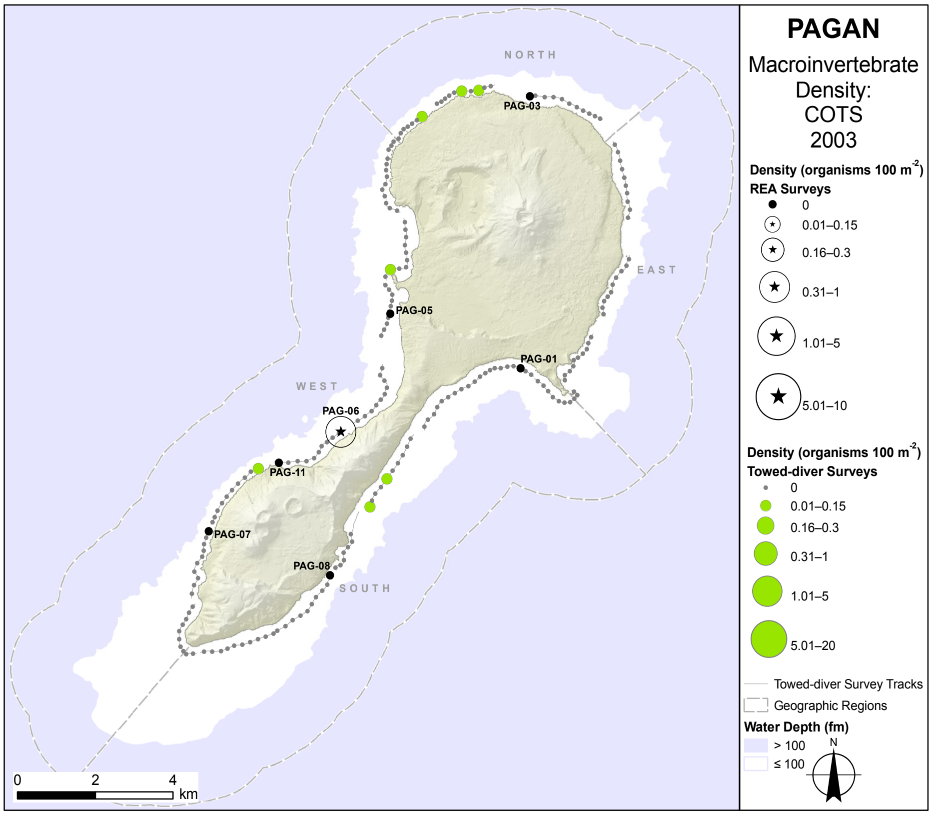


Figure 13.7.1e. Densities (organisms 100 m^{-2}) of COTS from REA and towed-diver benthic surveys of forereef habitats conducted around Pagan during MARAMP 2003.

During MARAMP 2005, no COTS were observed at the 9 REA sites surveyed around Pagan; however, high numbers of COTS were recorded in all but 1 of the 17 towed-diver surveys. The majority of COTS observed were concentrated in the east region and in the southern half of the south region. The islandwide mean density of COTS from towed-diver surveys was 0.24 organisms 100 m^{-2} (SE 0.05). Among all towed-diver surveys around this island, the survey completed in the south region between South Point and Buritoma in the south region had the highest mean density with 0.89 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 5.22 organisms 100 m^{-2} (Fig. 13.7.1f). The second-greatest mean density of COTS from a towed-diver survey was 0.75 organisms 100 m^{-2}, recorded between Buritoma and Fuwaebosu in the south region; segment densities ranged from 0 to 4.16 organisms 100 m^{-2}. The survey in the east region just north of Hira Rock had the third-greatest mean density with 0.68 organisms 100 m^{-2}; segment densities ranged from 0 to 2.86 organisms 100 m^{-2}.

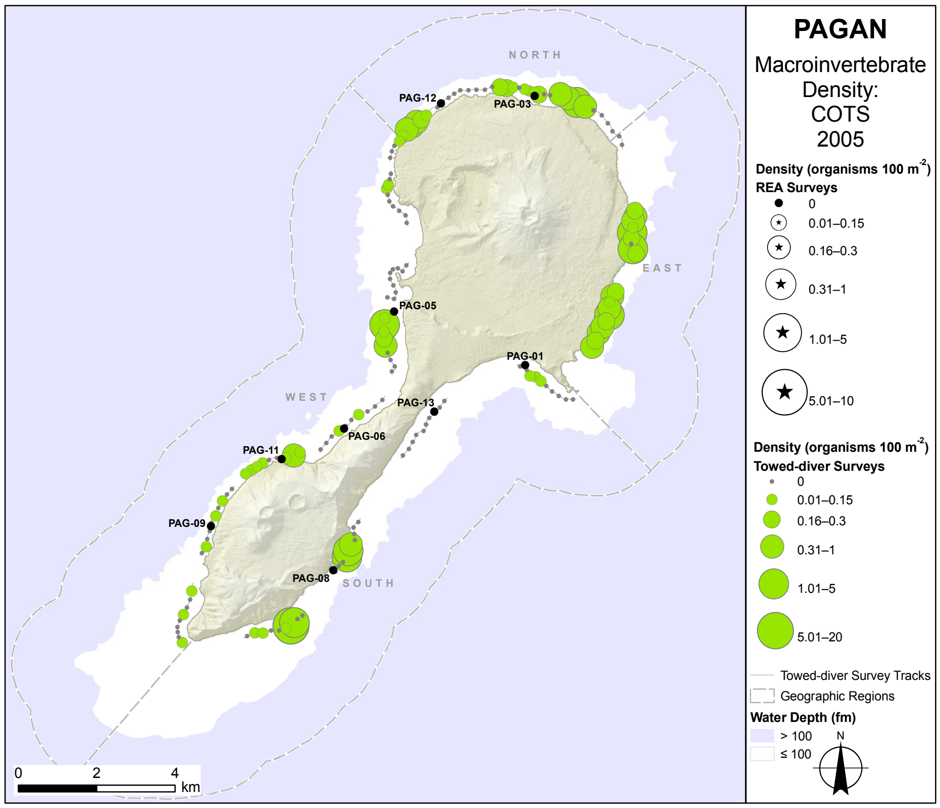


Figure 13.7.1f. Densities (organisms 100 m^{-2}) of COTS from REA and towed-diver benthic surveys of forereef habitats conducted around Pagan during MARAMP 2005.

During MARAMP 2007, COTS were observed at 3 of the 8 REA sites surveyed and in all 16 towed-diver surveys conducted around Pagan. The overall mean density of COTS from REA surveys was 0.33 organisms 100 m^{-2} (SE 0.15), and the islandwide mean density from towed-diver surveys was 0.08 organisms 100 m^{-2} (SE 0.01). The same COTS density was found at PAG-03 and PAG-12 in the north region and PAG-11 in the west region: 0.33 organisms 100 m^{-2} (Fig. 13.7.1.g). Among all towed-diver surveys around this island, the survey completed in the west region south of Dekairu had the highest mean density with 0.2 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 1.74 organisms 100 m^{-2}. The second-greatest mean density of COTS from a towed-diver survey was 0.17 organisms 100 m^{-2}, recorded in the east region north of Hira Rock; segment densities ranged from 0.09 to 0.44 organisms 100 m^{-2}. The survey in the south region between Togari Rock and Degusa had the third-greatest density with 0.17 organisms 100 m^{-2}; segment densities ranged from 0 to 0.82 organisms 100 m^{-2}.

Towed-diver surveys suggested low daytime densities of COTS during MARAMP 2003 and 2007 but high COTS densities during MARAMP 2005 around Pagan, compared to the rest of the Mariana Archipelago (Fig. 13.7.1h). This temporal pattern from towed-diver surveys suggests a potential recruitment pulse of COTS to Pagan between MARAMP 2003 and 2005. A greater percentage of forereef habitats was surveyed in 2003 than in other years, with 21 towed-diver surveys, yet these surveys recorded virtually no COTS with an islandwide mean density of 0.002 organisms 100 m^{-2}. The mean density of COTS observed from towed-diver surveys conducted around Pagan increased to 0.24 organisms 100 m^{-2} in 2005 and then declined to 0.08 organisms 100 m^{-2} by 2007.

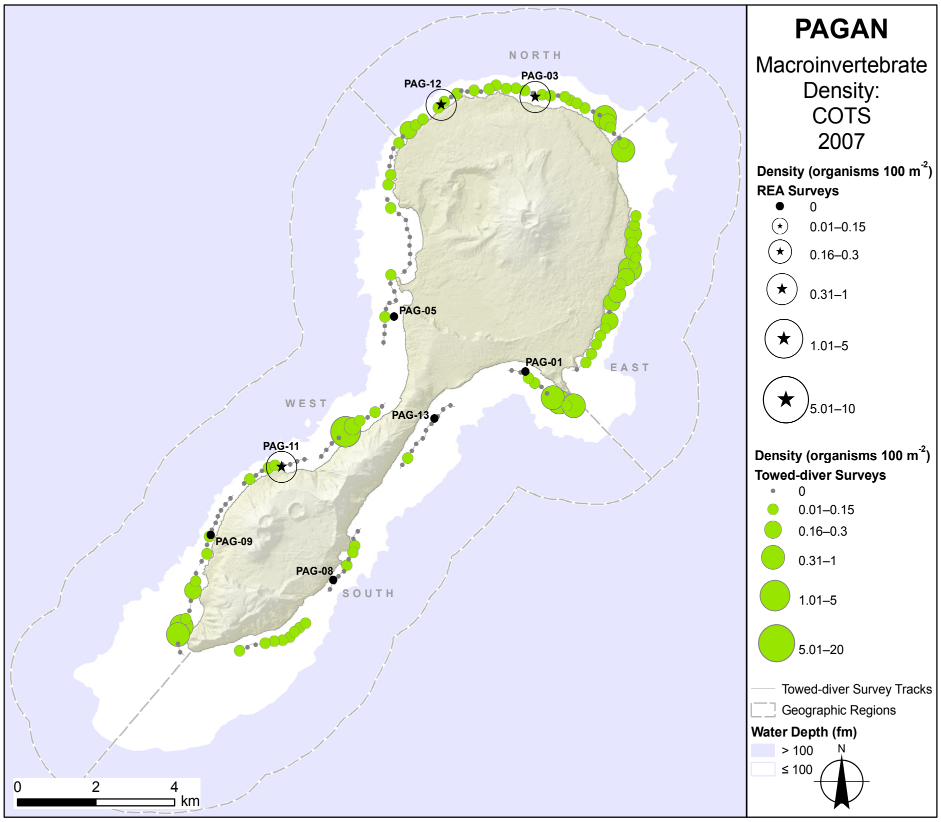


Figure 13.7.1g. Densities (organisms 100 m^{-2}) of COTS from REA and towed-diver benthic surveys of forereef habitats conducted around Pagan during MARAMP 2007.

Given that these corallivorous seastars can decimate a reef, understanding whether their observed densities signify an outbreak is important. By means of a manta-tow technique—which uses snorkel divers as observers in a manner similar to the procedure established for using scuba divers to conduct MARAMP towed-diver surveys—Moran and De'ath (1992) defined a potential outbreak as a reef area where the density of *A. planci* was > 1500 organisms km^{-2} (0.15 organisms 100 m^{-2}) and the level of dead coral present was at least 40%. Using this definition only in terms of density and considering each towed-diver survey as an individual reef area, localized areas with relatively high densities of COTS that suggest that they were undergoing an outbreak were found during MARAMP 2005 and 2007.

The aforementioned density criterion was met for 7 towed-diver surveys, conducted in the south, east, and north regions during MARMP 2005, with mean COTS densities of 0.24–0.87 organisms 100 m^{-2}. The south region had the greatest concentration of COTS in 2005. In 2007, 3 towed-diver surveys had densities > 0.15 organisms 100 m^{-2}, all located on reefs along the northern half Pagan. However, COTS densities from these surveys, with means of 0.17–0.21 organisms 100 m^{-2}, were lower than values recorded in 2005.

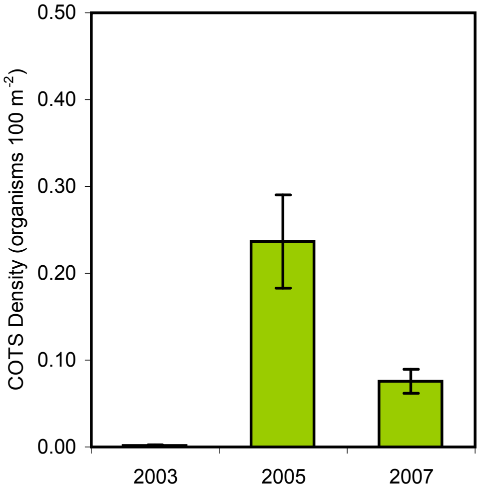
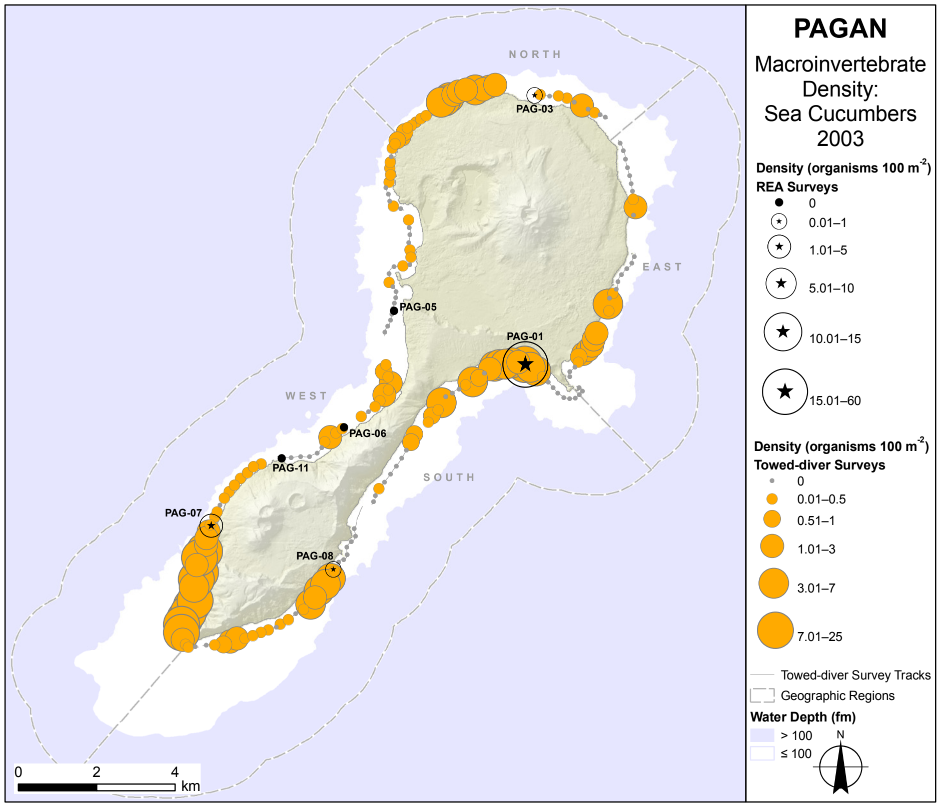


Figure 13.7.1h. Temporal comparison of COTS mean densities (organisms m^{-2}) from towed-diver benthic surveys conducted on forereef habitats around Pagan during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Sea Cucumbers

During MARAMP 2003, sea cucumbers were observed at 4 of the 7 REA sites surveyed and in 20 of the 21 towed-diver surveys conducted around Pagan. The overall mean density of sea cucumbers from REA surveys was 8.71 organisms 100 m^{-2} (SE 7.89), and the islandwide mean density from towed-diver surveys was 1.22 organisms 100 m^{-2} (SE 0.16). Survey results suggest that sea cucumbers were most abundant at PAG-01 in the south region east of Degusa with 26 organisms 100 m^{-2} (Fig. 13.7.1i). All the sea cucumbers recorded at this site were species of the genus *Stichopus*. The only other genus observed at REA sites was *Actinopyga*. Among all towed-diver surveys around this island, the survey completed

Figure 13.7.1i. Densities (organisms 100 m^{-2}) of sea cucumbers from REA and towed-diver benthic surveys of forereef habitats conducted around Pagan during MARAMP 2003.



around South Point had the highest mean density of sea cucumbers with 6.06 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 10.51 organisms 100 m^{-2}. The second-greatest mean density of sea cucumbers from a towed-diver survey was 4.64 organisms 100 m^{-2}, recorded north of South Point near Sarahai in the west region; segment densities ranged from 0 to 9.58 organisms 100 m^{-2}.

During MARAMP 2005, sea cucumbers were observed at 5 of the 9 REA sites surveyed and in all 17 towed-diver surveys conducted around Pagan (Fig. 13.7.1j). The overall mean density of sea cucumbers from REA surveys was 4 organisms 100 m^{-2} (SE 2.09), and the islandwide mean density from towed-diver surveys was 0.38 organisms 100 m^{-2} (SE 0.06). Species from the genus *Stichopus* represented 86% of sea cucumbers recorded in 2005 at Pagan during REA surveys, and species of the genera *Actinopyga*, *Holothuria*, and *Bohadschia* were also observed. Survey results suggest sea cucumbers were most prevalent at PAG-01 east of Degusa in the south region with 26 organisms 100 m^{-2}, all of them from the genus *Stichopus*. Among all towed-diver surveys around this island, the survey completed in the east region north of Sengao Peninsula had the highest mean density of sea cucumbers with 1.62 organisms 100 m^{-2}; segment densities from this survey ranged from 0.29 to 2.25 organisms 100 m^{-2}. The second-greatest mean density of sea cucumbers from a towed-diver survey was 1.49 organisms 100 m^{-2}, recorded in the south region between Degusa and Togari Rock; segment densities ranged from 0 to 4.17 organisms 100 m^{-2}.

During MARAMP 2007, sea cucumbers were observed at 6 of the 8 REA sites surveyed and in all 16 of the towed-diver surveys conducted around Pagan. The overall mean density from REA surveys was 4.71 organisms 100 m^{-2} (SE 2.31), and the islandwide mean density of 0.81 organisms 100 m^{-2} (SE 0.1). Species from the genus *Stichopus* represented 90% of sea cucumbers recorded in 2007 at Pagan during REA surveys. Survey results suggest sea cucumbers were most abundant at PAG-12 in the north region with 16.33 organisms 100 m^{-2} (Fig. 13.7.1k), and 96% of them were species from the genus *Stichopus*. Species from the genera *Holothuria* and *Pearsonothuria* were also observed at PAG-12. PAG-01 in the south region east of Degusa had the second-greatest mean density with 13.67 organisms 100 m^{-2}. Species of the genus *Stichopus* accounted for 95% of sea cucumbers observed at this site, and species of the genera *Bohadschia* and *Pearsonothuria* were also recorded.

Among all towed-diver surveys conducted around Pagan in 2007, the survey completed in the south region, east of Piarama, had the highest mean density of sea cucumbers with 2.07 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 9.74 organisms 100 m^{-2}. The second-greatest mean density of sea cucumbers from a towed-diver survey was 1.87 organisms 100 m^{-2}, recorded in the north region near Tarage; segment densities ranged from 0.57 to 3.37 organisms 100 m^{-2}.

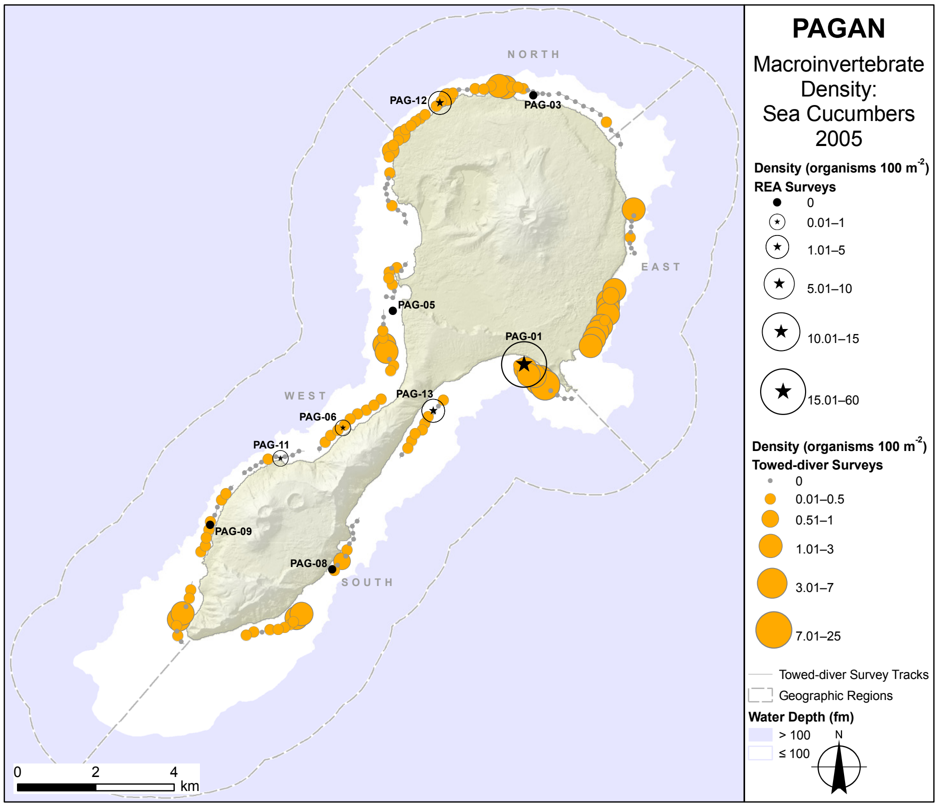


Figure 13.7.1j. Densities (organisms 100 m^{-2}) of sea cucumbers from REA and towed-diver benthic surveys of forereef habitats conducted around Pagan during MARAMP 2005.

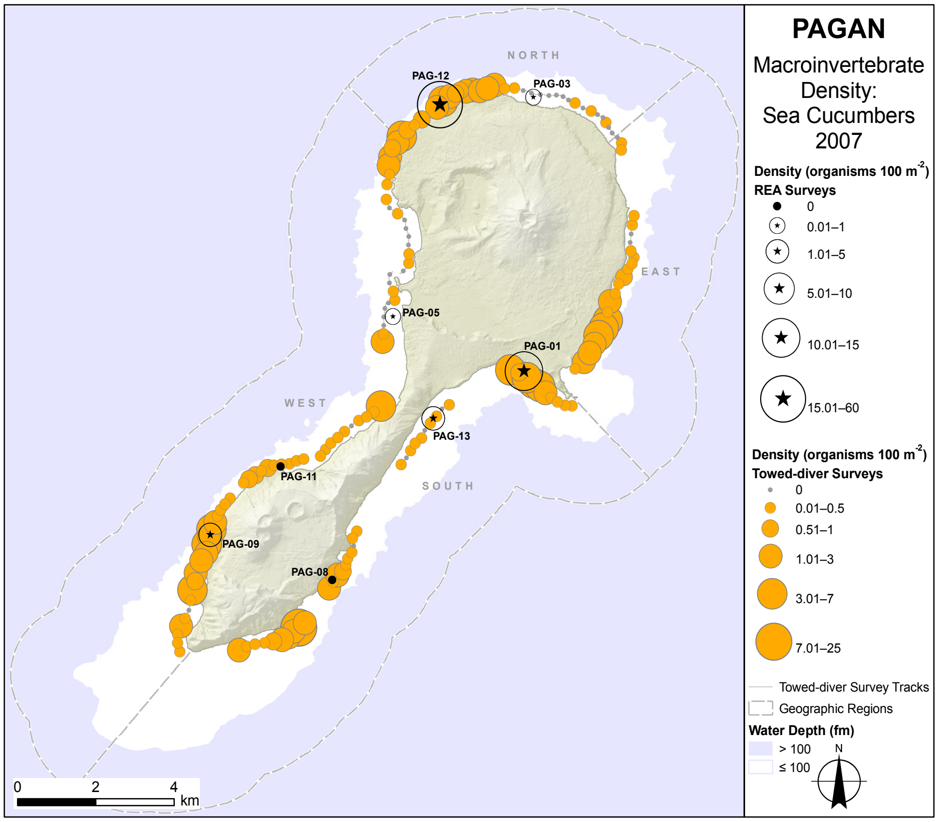


Figure 13.7.1k. Densities (organisms 100 m^{-2}) of sea cucumbers from REA and towed-diver benthic surveys of forereef habitats conducted around Pagan during MARAMP 2007.

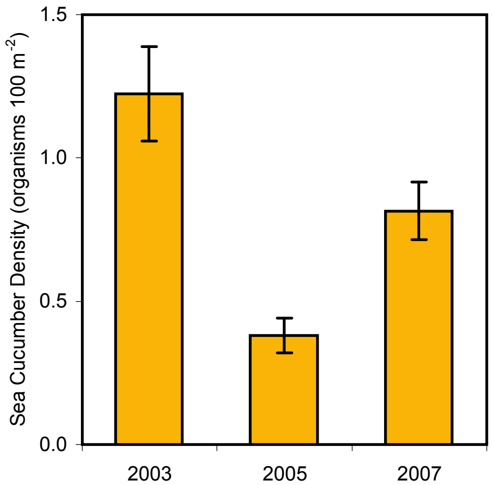


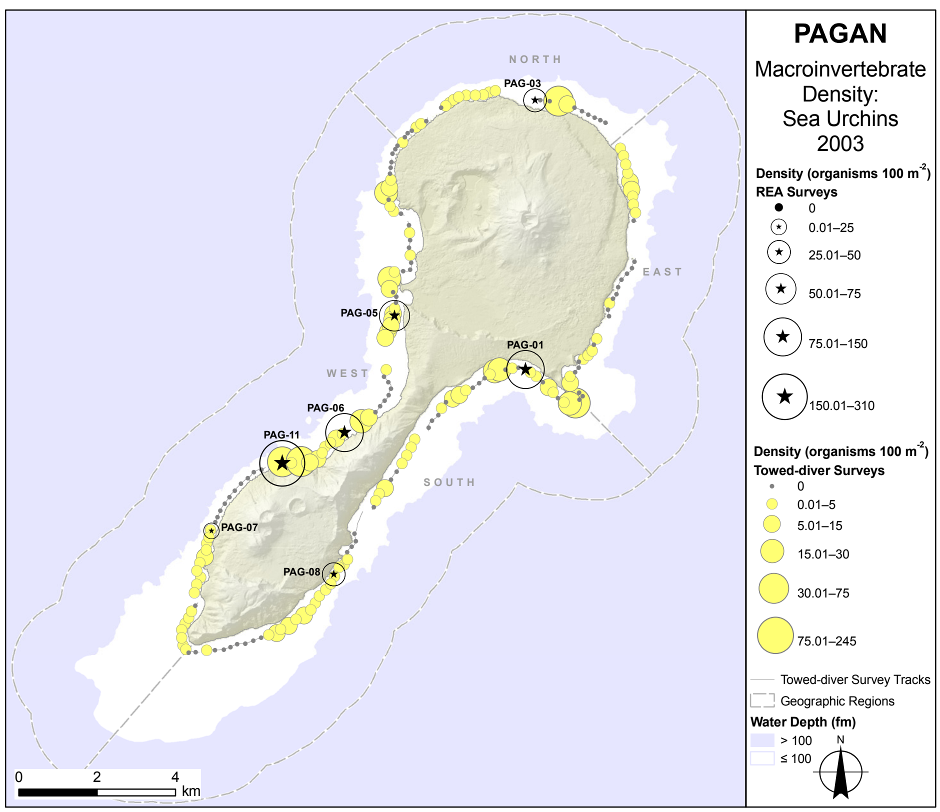
Figure 13.7.1l. Temporal comparison of mean densities (organisms m^{-2}) of sea cucumbers from towed-diver benthic surveys conducted on forereef habitats around Pagan during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Towed-diver surveys suggested that daytime abundance of sea cucumbers was more or less uniformly distributed around Pagan during the 3 MARAMP survey years. The overall observed mean density of sea cucumbers around Pagan decreased from 2003 to 2005 and then increased from 2005 to 2007 (Fig. 13.7.1l). These changes may result from differences in survey effort or other factors and are not necessarily indicative of changes in the population structure of sea cucumbers (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys"). The number of towed-diver surveys decreased from 21 in 2003 to 17 and 16 in 2005 and 2007. Also, towed-diver surveys covered more habitat around the southern tip of Pagan in 2003 than in 2005 and 2007; this area had the greatest density of sea cucumbers with 6.06 organisms 100 m^{-2}.

Sea Urchins

During MARAMP 2003, sea urchins were observed at all 7 REA sites surveyed and in 20 of the 21 towed-diver surveys conducted around Pagan. The overall mean density of sea urchins from REA surveys was 80.43 organisms 100 m^{-2} (SE 27.81), and the islandwide mean density from towed-diver surveys was 3.08 organisms 100 m^{-2} (SE 0.48). Survey results suggest that sea urchins were most abundant at PAG-11 near Pontanjaburo in the west region with 226 organisms 100 m^{-2} (Fig. 13.7.1m). Rock-boring urchin species of the genus *Echinostrephus* accounted for 95% of the observed urchins at this site and species of the genus *Echinothrix*, *Echinometra*, and *Diadema* were recorded in low numbers, compared

Figure 13.7.1m. Densities (organisms 100 m^{-2}) of sea urchins from REA and towed-diver benthic surveys of forereef habitats conducted around Pagan during MARAMP 2003.



to other sites surveyed in the Mariana Archipelago. PAG-01 had the second-greatest density of sea urchins with 112 organisms 100 m^{-2}. Four genera were recorded at this site: *Echinostrephus*, *Echinometra*, *Diadema,* and *Echinothrix.* The rock-boring urchin *Echinostrephus* was also the dominant genus of sea urchins at this site, where it accounted for 93.7% of urchin observations.

Among all towed-diver surveys conducted around Pagan in 2003, the survey completed in the west region, south of Dekairu, had the highest mean density of sea urchins with 11.22 organisms 100 m^{-2}; segment densities from this survey ranged from 2.13 to 32.89 organisms 100 m^{-2}. The second-greatest mean density from a towed-diver survey was 9.67 organisms 100 m^{-2}, recorded between Togari Rock and Degusa in the south region; segment densities ranged from 0 to 49.5 organisms 100 m^{-2}.

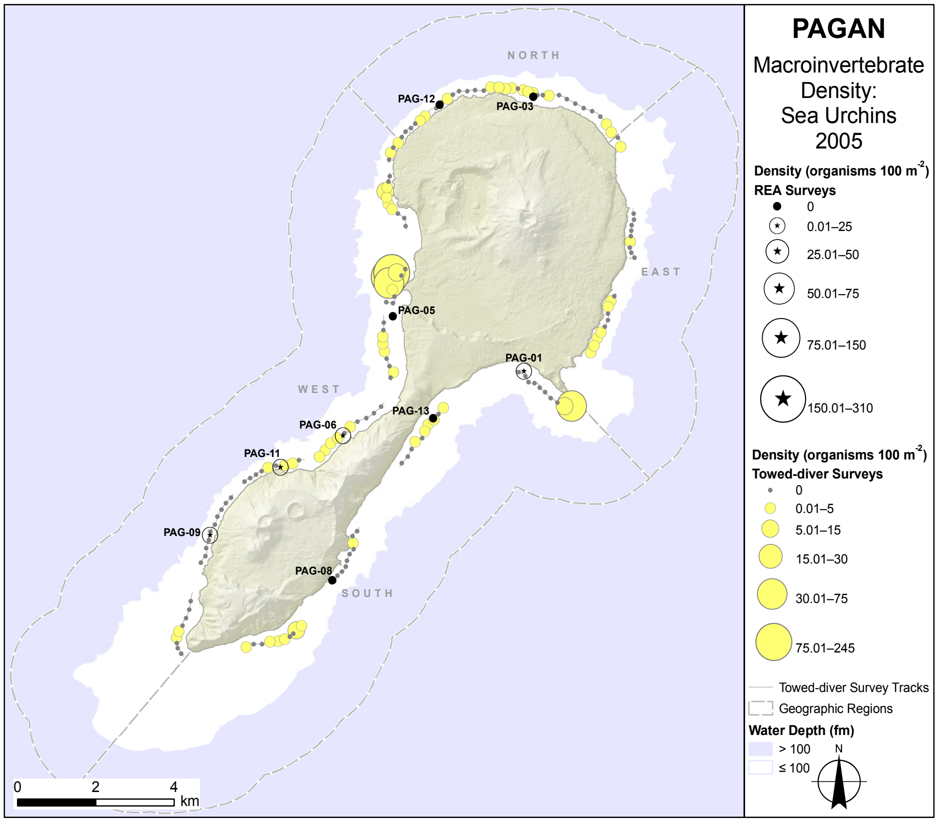
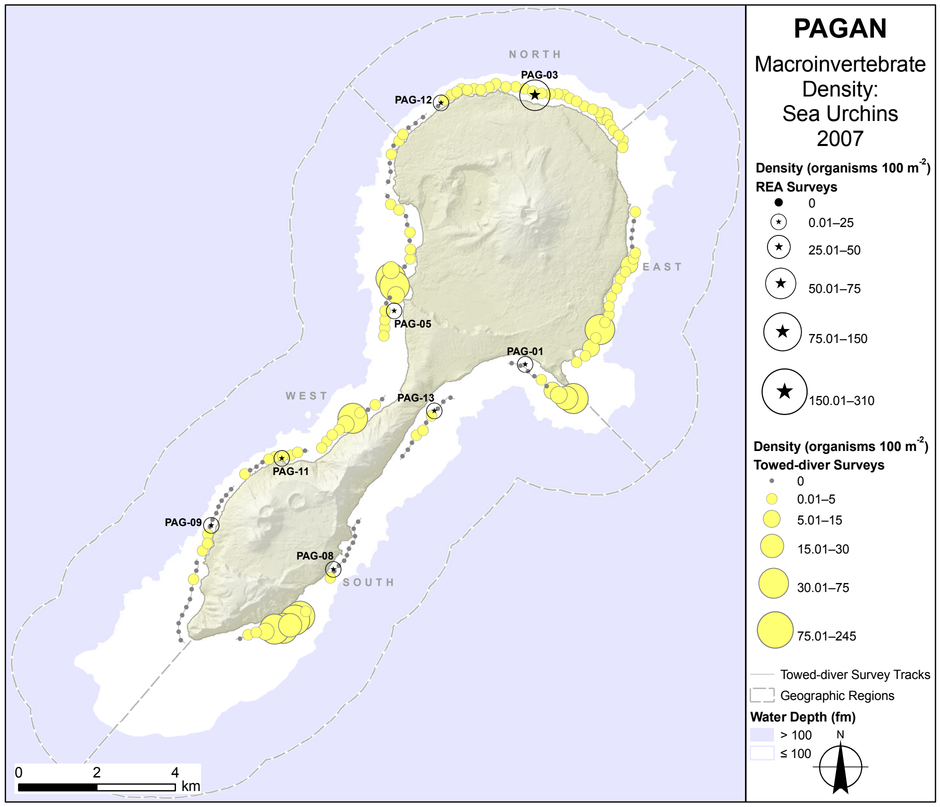


Figure 13.7.1n. Densities (organisms 100 m^{-2}) of sea urchins from REA and towed-diver benthic surveys of forereef habitats conducted around Pagan during MARAMP 2005.

During MARAMP 2005, sea urchins were observed at 4 of the 9 REA sites surveyed and in 15 of the 17 towed-diver surveys conducted around Pagan. The overall mean density of sea urchins from REA surveys was 0.89 organisms 100 m^{-2} (SE 0.39), and the islandwide mean density from towed-diver surveys was 2.15 organisms 100 m^{-2} (SE 0.82). Survey results suggest sea urchins were most prevalent at PAG-06 in the west region south of Dekairu with 3 organisms 100 m^{-2} (Fig. 13.7.1n). Among all towed-diver surveys around this island, the survey completed around Bandera Peninsula in the west region had the highest mean density of sea urchins with 21.5 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 84.34 organisms 100 m^{-2}. The second-greatest mean density from a towed-diver survey was 6.84 organisms 100 m^{-2}, recorded between Togari Rock and Degusa in the south region; segment densities ranged from 3.38 to 38.92 organisms 100 m^{-2}.

During MARAMP 2007, sea urchins were observed at all 8 REA sites surveyed and in all 16 towed-diver surveys conducted around Pagan. The overall mean density of sea urchins from REA surveys was 11.04 organisms 100 m^{-2} (SE 6.44), and the islandwide mean density from towed-diver surveys was 3.9 organisms 100 m^{-2} (SE 0.83). Survey results suggest that sea urchins were most abundant at PAG-03 in the north region near Tarage with 52 organisms 100 m^{-2} (Fig. 13.7.1o). Rock-boring urchins of the genus *Echinostrephus* accounted for 97% of recorded sea urchins at this site. PAG-05 had the second-greatest density of sea urchins with 23.67 organisms 100 m^{-2}. The rock-boring urchin *Echinostrephus* was the dominant urchin at this site, where it accounted for 98.6% of observations. Overall, 3 genera were observed on forereef habitats around Pagan: *Echinostrephus*, *Echinothrix*, and *Diadema.*

Figure 13.7.1o. Densities (organisms 100 m^{-2}) of sea urchins from REA and towed-diver benthic surveys of forereef habitats conducted around Pagan during MARAMP 2007.



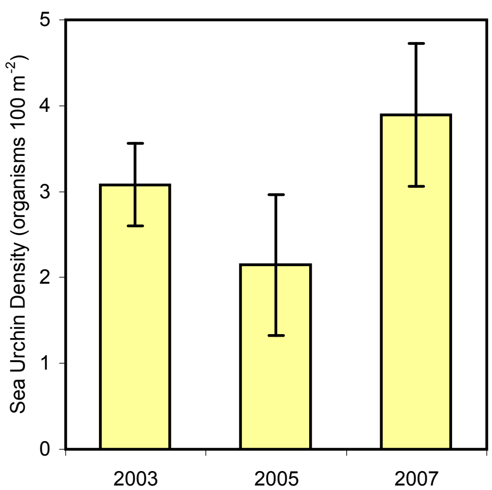


Figure 13.7.1p. Temporal comparison of mean densities (organisms m^{-2}) of sea urchins from towed-diver benthic surveys conducted on forereef habitats around Pagan during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Among all towed-diver surveys conducted around Pagan in 2007, the survey completed in the south region near Piarama had the highest mean density of sea urchins with 23.06 organisms 100 m^{-2}; segment densities for this survey ranged from 0 to 55.70 organisms 100 m^{-2}. The second-greatest mean density from a towed-diver survey was 10.14 organisms 100 m^{-2}, recorded in the west region near Bandera Peninsula; segment densities ranged from 0 to 45.85 organisms 100 m^{-2}. The towed-diver survey conducted between Togari Rock and Degusa in the south region had the third-greatest mean density at 8.74 organisms 100 m^{-2}; segment densities ranged from 0 to 49.79 organisms 100 m^{-2}.

Towed-diver surveys suggested low daytime abundance of sea urchins around Pagan, compared to the rest of the Mariana Archipelago. Overall mean sea urchin densities from towed-diver surveys varied slightly between MARAMP survey years (Fig. 13.7.1p). Minor fluctuations in densities are not necessarily indicative of changes in the population structure of sea cucumbers (for information about data limitations, see Chapter 2: “Methods and Operational Background,” Section 2.4: “Reef Surveys”).

13.8 Reef Fishes

13.8.1 Reef Fish Surveys

Large-fish Biomass

During MARAMP 2003, 21 towed-diver surveys for large fishes (≥ 50 cm in total length [TL]) were conducted in forereef habitats around the island of Pagan. The islandwide estimated mean biomass of large fishes, calculated as weight per unit area, was 0.87 kg 100 m^{-2} (SE 0.18), a high value compared to levels found around other islands in the Mariana Archipelago. Values of large-fish biomass were high in most survey areas around Pagan, compared to survey results at other islands in the Mariana Archipelago, and no clear spatial patterns were seen in the distribution of biomass (Fig. 13.8.1a). Reef sharks (Carcharhinidae), nurse sharks (Ginglymostomatidae), and snappers (Lutjanidae) contributed 58% to overall large-fish biomass around Pagan. Sharks alone accounted for 26% or 0.23 kg 100 m^{-2} of large-fish biomass with the tawny nurse shark (*Nebrius ferrugineus*) contributing 78% of shark biomass. During this survey period, 25 sharks were observed: 13 whitetip reef sharks (*Triaenodon obesus*) and 12 tawny nurse sharks. Snappers accounted for 32% of overall large-fish biomass. The twinspot snapper (*Lutjanus bohar*) contributed 66% or 0.18 kg 100 m^{-2} of snapper biomass with 155 individuals recorded in 2003. Jacks (Carangidae) and parrotfishes (Scaridae) also were common, accounting for 9% and 10% of islandwide large-fish biomass. Biomass values for large fishes were highest along the northwestern coast, where sharks, snappers and stingrays (Dasyatidae) commonly were observed.

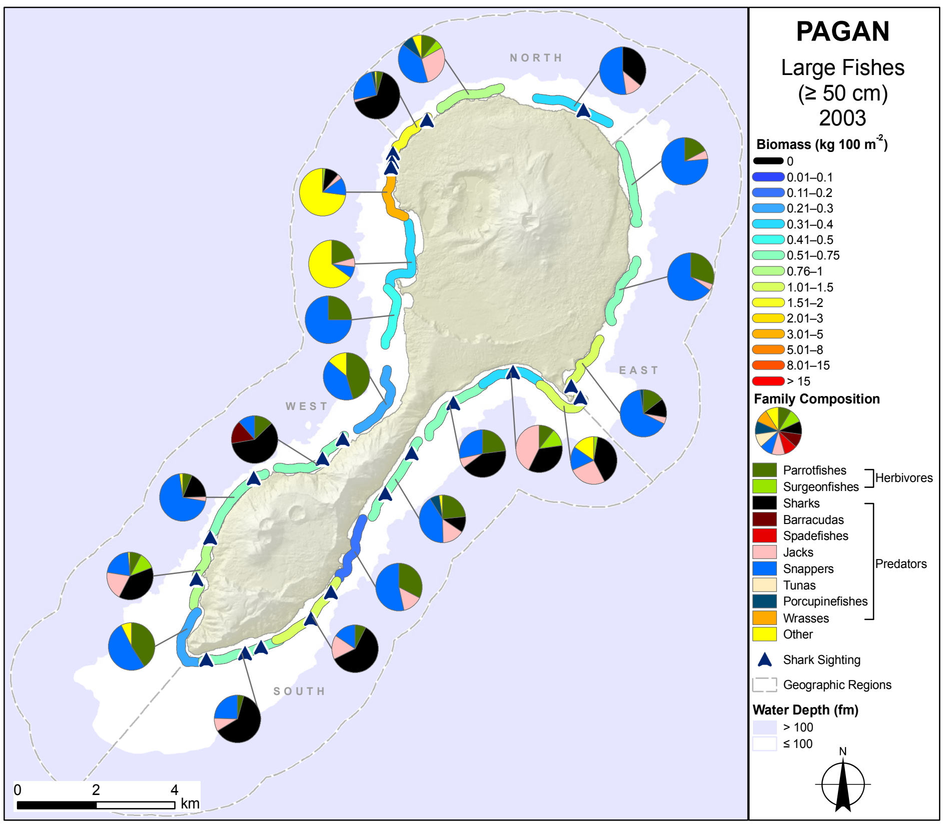


Figure 13.8.1a Observations of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}), family composition, and shark sightings from towed-diver fish surveys of forereef habitats conducted around Pagan during MARAMP 2003. Each blue triangle represents a sighting of one or more sharks recorded inside or outside of the survey area over which it is shown

During MARAMP 2005, 17 towed-diver surveys for large fishes (≥ 50 cm in TL) were conducted in forereef habitats around Pagan. The islandwide estimated mean biomass of large fishes was lower than the value found in 2003 with 0.37 kg 100 m^{-2} (SE 0.08). Sharks accounted for the largest proportion (22%) of overall large-fish biomass. The tawny nurse shark contributed 60% of shark biomass and 0.05 kg 100 m^{-2} to overall large-fish biomass. During this survey period, 14 sharks were observed: 10 whitetip reef sharks, 3 tawny nurse sharks, and 1 blacktip reef shark (*Carcharhinus melanopterus*). Jacks and snappers also were commonly recorded around Pagan, each accounting for 20% of overall large-fish biomass. The bigeye trevally (*Caranx sexfasciatus*) contributed the greatest proportion of jack biomass, with a school of 45 individuals recorded during a single survey along the northwestern coast. Consistent with observations made in 2003, the twinspot snapper was the dominant snapper species by biomass, accounting for 75% of snapper biomass and

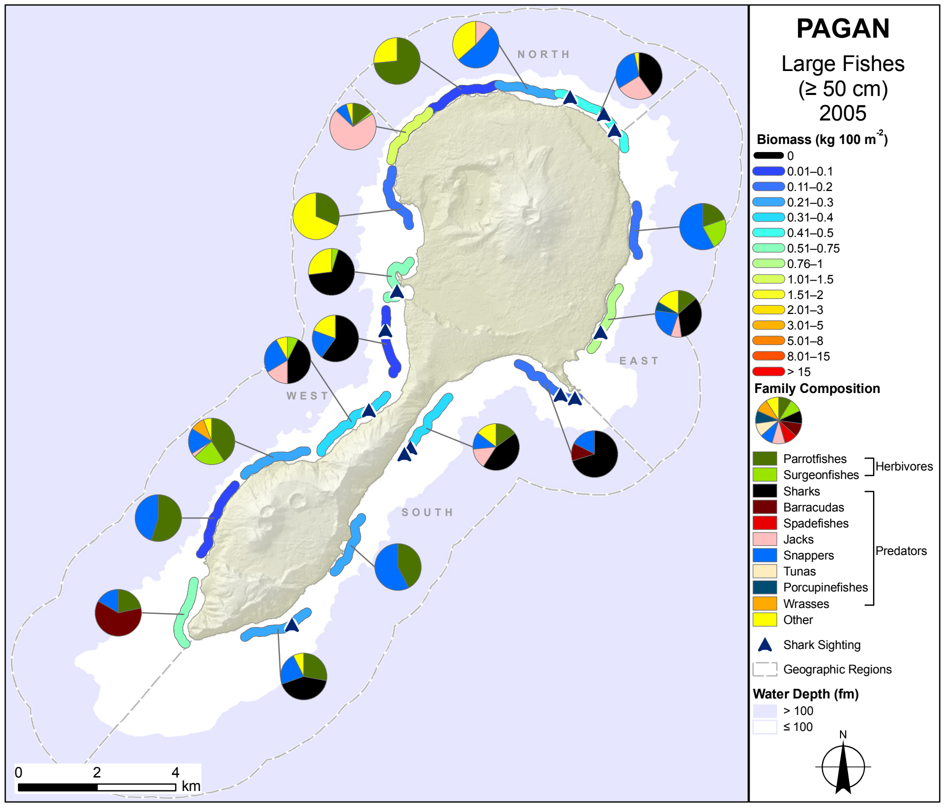


Figure 13.8.1b. Observations of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}), family composition, and shark sightings from towed-diver fish surveys of forereef habitats conducted around Pagan during MARAMP 2005. Each blue triangle represents a sighting of one or more sharks recorded inside or outside of the survey area over which it is shown.

0.06 kg 100 m^{-2} of overall large-fish biomass. Also similar to survey results from 2003, biomass values for large fishes were highest along the northwestern coast, where the school of bigeye jacks was seen (Fig. 13.8.1b).

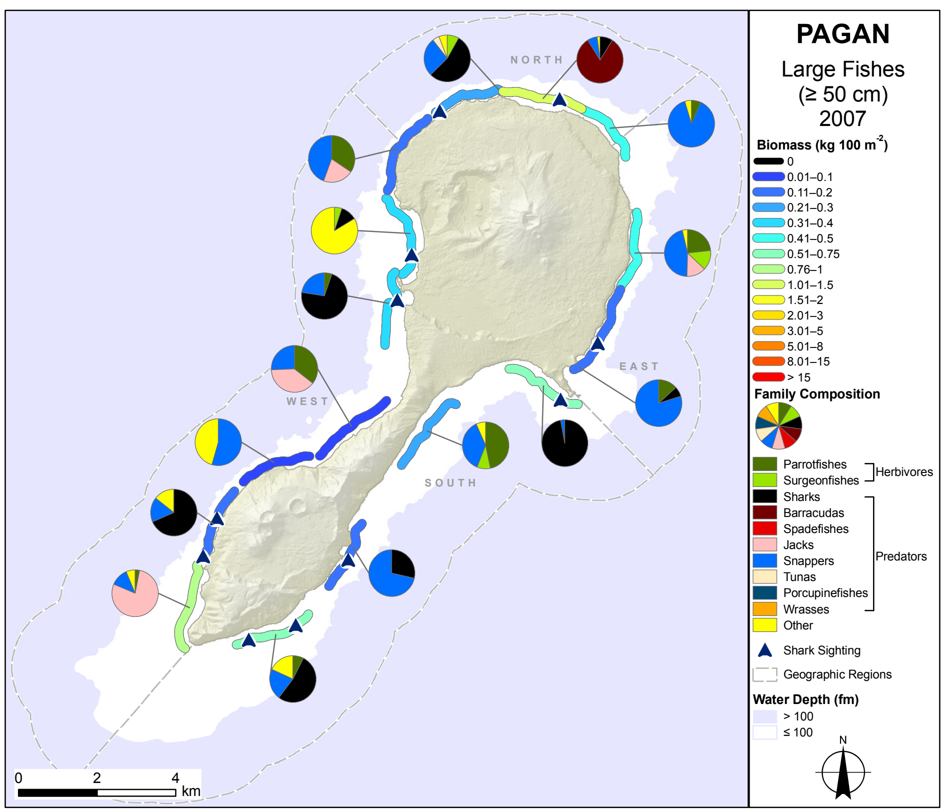


Figure 13.8.1c. Observations of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}), family composition, and shark sightings from towed-diver fish surveys conducted of forereef habitats around Pagan during MARAMP 2007. Each blue triangle represents a sighting of one or more sharks recorded inside or outside of the survey area over which it is shown.

During MARAMP 2007, 16 towed-diver surveys for large fishes (≥ 50 cm in TL) were conducted in forereef habitats around Pagan. The islandwide estimated mean biomass of large fishes was 0.41 kg 100 m^{-2} (SE 0.09), similar to survey results from 2005. Consistent with previous survey periods, sharks accounted for the largest proportion (27%) of large-fish biomass. Tawny nurse sharks contributed 79% of shark biomass and 0.09 kg 100 m^{-2} to overall large-fish biomass. During this survey period, 12 sharks were observed, all of them benthic dwelling species: 7 whitetip reef sharks and 5 tawny nurse sharks. Snappers accounted for the second-greatest proportion (25%) of large-fish biomass. The twinspot snapper was the most abundant snapper species, contributing 69% or 0.07 kg 100 m^{-2} of snapper biomass. Barracudas (Sphyraenidae) and jacks also were common, accounting for 18% and 11% of overall large-fish biomass. Biomass values for large fishes were highest in the north region, where a school of Heller's barracuda (*Sphyraena helleri*) was observed during a single survey (Fig. 13.8.1c).

Large-fish biomass from towed-diver surveys of forereef habitats was distributed fairly evenly around Pagan in each of the 3 MARAMP survey years; however, values were slightly elevated in the west and north regions versus other areas surveyed at Pagan. Islandwide mean biomass of large fishes around Pagan was highest in 2003 with 0.87 kg 100 m^{-2} (SE 0.18), dropping to 0.37 kg 100 m^{-2} (SE 0.08) in 2005 and 0.41 kg 100 m^{-2} (SE 0.09) in 2007 (Fig. 13.8.1d). Averaged across the 3 survey years, large-fish biomass around Pagan was 0.55 kg 100 m^{-2} (SE 0.16), below the average for the northern islands of the Mariana Archipelago. Sharks accounted for > 20% of overall large-fish biomass in each of the 3 MARAMP survey years, and benthic dwelling species like whitetip reef sharks and tawny nurse sharks were the most abundant. Snappers also were common, and the twinspot snapper was the major snapper species by biomass in each survey period.

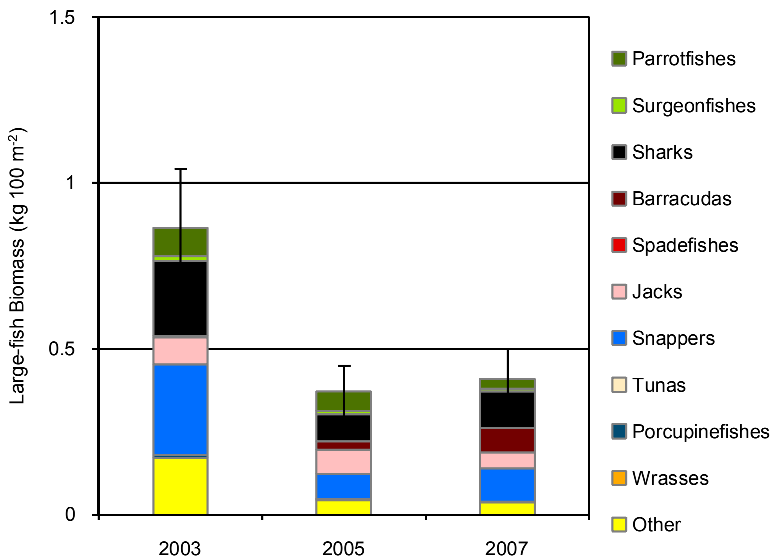
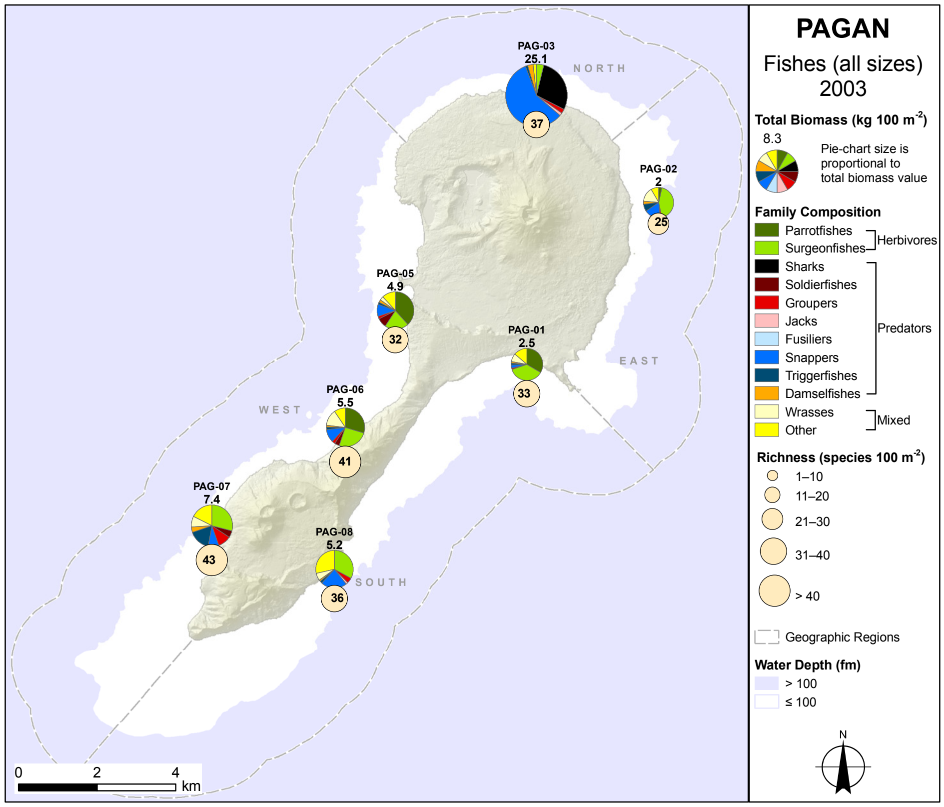


Figure 13.8.1d. Temporal comparison of mean values of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}) from towed-diver fish surveys of forereef habitats conducted around Pagan during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Total Fish Biomass and Species Richness

Mean total fish biomass for the 7 REA sites surveyed in forereef habitats at Pagan during MARAMP 2003 was 7.52 kg 100 m^{-2} (SE 3.01). The highest biomass of 25.07 kg 100 m^{-2} was observed at PAG-03 in the north region near Tarage, where 3 whitetip reef sharks were observed. The other sites surveyed at this island had more similar values of 2.03–7.37 kg 100 m^{-2} (Fig. 13.8.1e). Nearly half of the total fish biomass at PAG-03 consisted of snappers and reef sharks. Snappers accounted for the greatest proportion (34%) of total fish biomass at Pagan. The twinspot snapper contributed 69% to snapper biomass and 2.04 kg 100 m^{-2} to total fish biomass. Reef sharks accounted for the second-greatest proportion (13%) of total fish biomass; the whitetip reef shark was the only shark species observed and contributed 1.01 kg 100 m^{-2} to total fish biomass. Surgeonfishes (Acanthuridae) were also common. There was evidence of a large recruitment of orangespine unicornfish (*Naso lituratus*), which accounted for the greatest proportion (33%) of surgeonfish biomass and 0.43 kg 100 m^{-2} of total fish biomass. Many newly recruited orangespine unicornfish appeared to be frail and in a compromised state. At some REA sites, numerous individuals were dead and littered across the seabed.

Figure 13.8.1e. Observations of total fish biomass (all species and size classes in kg 100 m^{-2}), family composition, and species richness (species 100 m^{-2}) from REA fish surveys using the belt-transect method in forereef habitats at Pagan during MARAMP 2003.



Based on REA surveys conducted during MARAMP 2003, species richness at Pagan ranged from 25 to 43 species 100 m^{-2}. The lowest diversity was seen at PAG-02 in the east region, and the highest diversity was found at PAG-07 in the west region. Wrasses (Labridae) composed the most represented family with 27 species observed. The ornate wrasse (*Halichoeres ornatissimus*) was the most abundant wrasse species. Damselfishes (Pomacentridae) were the most abundant taxa of fishes overall with the Vanderbilt's chromis (*Chromis vanderbilti*) dominating counts at 18 individuals 100 m^{-2}.

Total fish biomass for the 9 REA sites surveyed in forereef habitats at Pagan during MARAMP 2005, with an overall sample mean of 9.28 kg 100 m^{-2} (SE 1.85), was similar to survey results at this island in 2003. The highest biomass of 19.25 kg 100 m^{-2} was found at PAG-06 in the west region (Fig. 13.8.1f). Surgeonfishes accounted for the largest proportion (37%) of total fish biomass. A small tawny nurse shark (100 cm in TL) was the only shark observed in 2005.

Based on REA surveys conducted during MARAMP 2005, species richness at Pagan was similar to the diversity recorded in 2003 with a range of 19–45 species 100 m^{-2}. The highest diversity in 2005 was found in the north region at PAG-12, which was not surveyed in 2003. The lowest diversity was seen at 2 sites: PAG-03 in the north region and PAG-08 in the south region. Wrasses composed the most represented family with 27 species recorded. Similar to observations made in 2003, the ornate wrasse was the most abundant wrasse species. Damselfishes were the most abundant taxa of fishes overall with the midget chromis (*Chromis acares*) dominating counts at 134 individuals 100 m^{-2}.

Total fish biomass for the 9 REA sites surveyed in forereef habitats at Pagan during MARAMP 2007, with an overall sample mean of 9.90 kg 100 m^{-2} (SE 2.29), was similar to biomass values observed in 2003 and 2005. The highest biomass of 25.19 kg 100 m^{-2} was found at PAG-12 in the north region, and the lowest biomass of 3.31 kg 100 m^{-2} was seen at site PAG-03, near Tarage and also in the north region (Fig. 13.8.1g). Similar to observations made in 2005, surgeonfishes accounted for the largest proportion (38%) of total fish biomass. The orangespot surgeonfish (*Acanthurus olivaceus*) accounted for the greatest proportion (37%) of surgeonfish biomass and 1.74 kg 100 m^{-2} of total fish biomass. The orangespine unicornfish also was common, accounting for the second-greatest proportion (18%) of surgeonfish biomass. Sharks were rare with 1 whitetip reef shark observed at PAG-11 in the west region.

Based on REA surveys conducted during MARAMP 2007, species richness at Pagan was similar to the diversity recorded in 2003 and 2005 with a range of 26–48 species 100 m^{-2}. The site with the highest species diversity in 2007, PAG-12 in the north region, also had the highest diversity in 2005. This site also had the highest total fish biomass in 2007. The lowest diversity was seen in the south region at PAG-08, although this site had the second-greatest total fish biomass. Wrasses composed the most represented family with 29 species recorded. Consistent with observations made in 2003 and 2005, the ornate wrasse was the most abundant wrasse species observed in 2007 with 10 individuals 100 m^{-2}. Damselfishes were the most abundant taxa of fishes with the midget chromis again dominating counts with 87 individuals 100 m^{-2}.

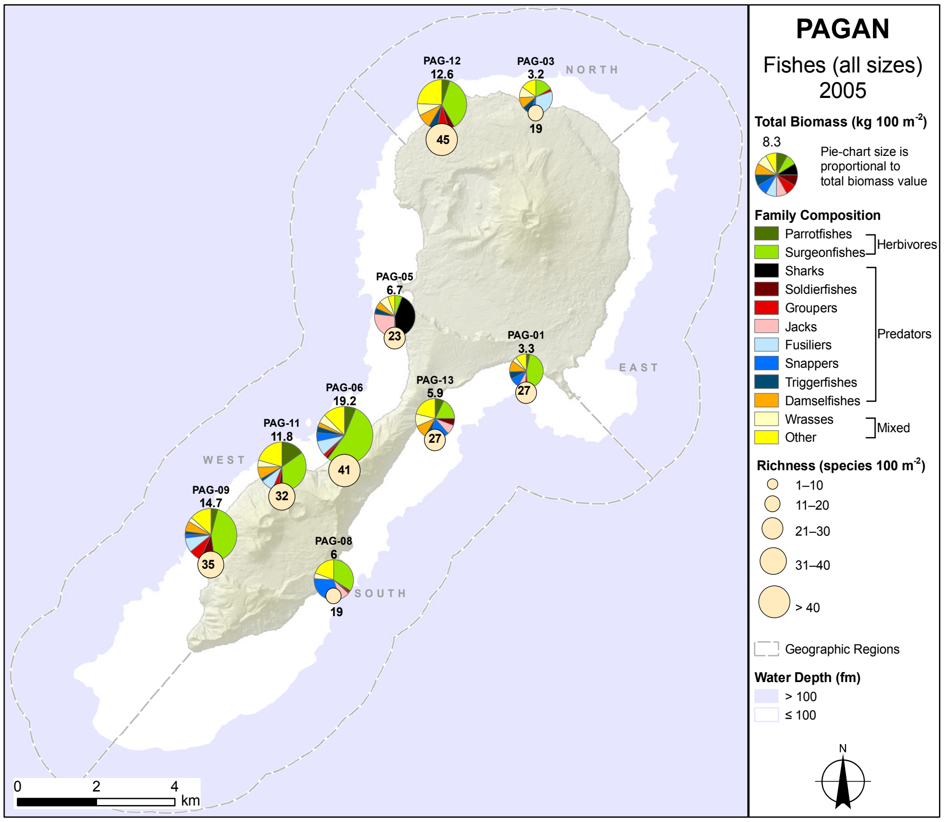


Figure 13.8.1f. Observations of total fish biomass (all species and size classes in kg 100 m^{-2}), family composition, and species richness (species 100 m^{-2}) from REA fish surveys using the belt-transect method in forereef habitats at Pagan during MARAMP 2005.

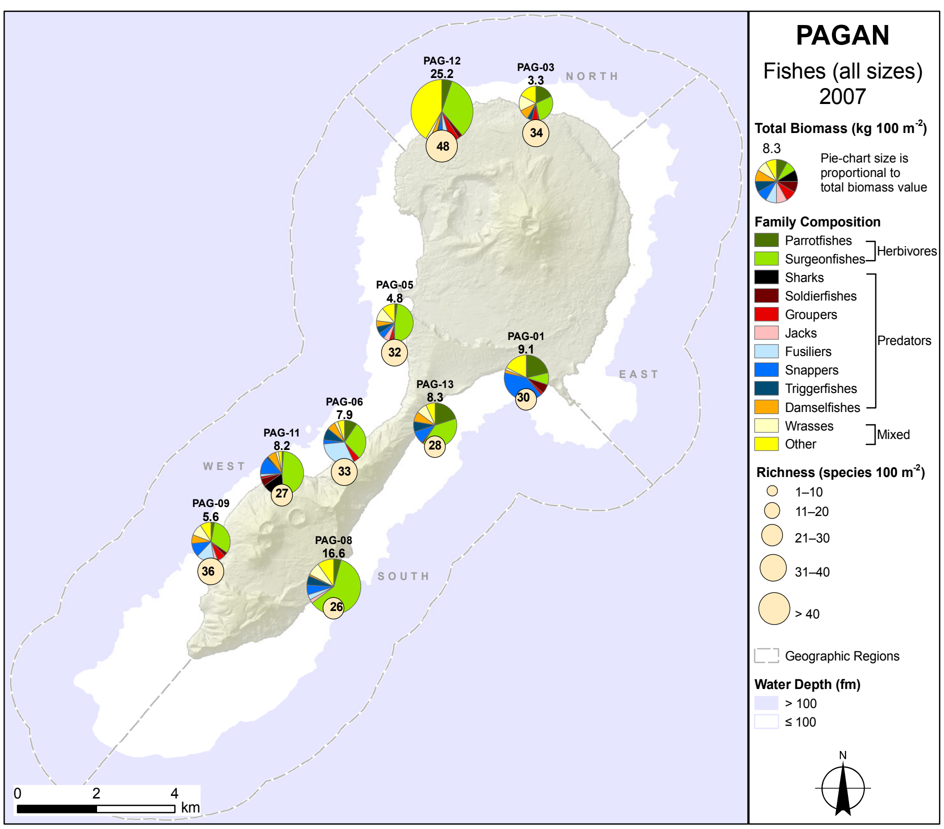
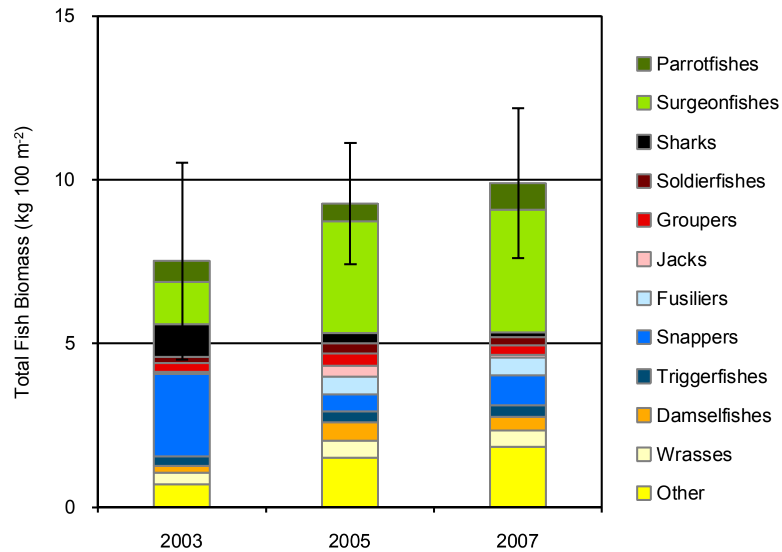


Figure 13.8.1g. Observations of total fish biomass (all species and size classes in kg 100 m^{-2}), family composition, and species richness (species 100 m^{-2}) from REA fish surveys using the belt-transect method in forereef habitats at Pagan during MARAMP 2007.

Total fish biomass for all REA sites surveyed at Pagan was consistently high (Fig. 13.8.1h) across the 3 MARAMP years, relative to biomass values observed at other islands in the Mariana Archipelago. Surgeonfishes accounted for the greatest proportion (nearly 40%) of overall total fish biomass from surveys conducted in 2005 and 2007. In 2003, however, fish biomass was dominated by snappers and reef sharks; 3 whitetip reef sharks were observed at PAG-03 in the north region near Tarage. Overall total fish biomass for Pagan, averaged across the 3 survey periods, was 8.90 kg 100 m^{-2} (SE 0.71), more than 3 times the observed biomass values for Guam and Saipan and slightly lower than average for the unpopulated islands of the Mariana Archipelago.

Species richness at Pagan was similar in the 3 MARAMP survey years, with an overall mean of 32.6 species 100 m^{-2} (SE 1.6).Wrasses compopsed the most represented family in each of the 3 survey periods with an average of 27 species recorded per year. The ornate wrasse was consistently the most abundant wrasse species observed. Damselfishes were the most abundant taxa of fishes overall, and the midget chromis and Vanderbilt's chromis were the most abundant damselfish species recorded over the 3 survey years.

Figure 13.8.1h. Temporal comparison of mean values of total fish biomass (all species and size classes in kg 100 m^{-2}) from REA fish surveys of forereef habitats conducted at Pagan during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.



13.9 Marine Debris

13.9.1 Marine Debris Surveys

During MARAMP 2003, 5 sightings of man-made objects and 2 sightings of wrecks were recorded in the 21 towed-diver surveys conducted on forereef habitats around the island of Pagan (Fig. 13.9.1a). Three anchors were observed adjacent to Marasu just north of the border between the north and west regions (for place-names and their locations, see Figure 13.2a in Section 13.2: "Survey Effort"). An unidentified aluminum structure and a shipwreck were recorded at 2 separate locations along Bandera Peninsula in the west region. An additional wreck, with propeller, engine, and anchor chain, was noted in the west region along this island's isthmus. Farther south in the west region, an unidentified steel object was observed north of Periiruu. No munitions or derelict fishing gear were identified in 2003.

During MARAMP 2005, no marine debris sightings were recorded in the 17 towed-diver surveys conducted on forereef habitats around Pagan.

During MARAMP 2007, 1 sighting of derelict fishing gear and 1 sighting of a wreck were recorded in the 16 towed-diver surveys conducted on forereef habitats around Pagan (Fig. 13.9.1b). One net was noted in the south region along this island's isthmus. A small wreck was recorded in a sandy area of low habitat complexity along Bandera Peninsula in the west region. No additional descriptive information was recorded, aside from the observation that live corals and algae were established on the wreck. No munitions or other man-made objects were identified in 2007.

Observations of debris are positive identifications, but absence of reports does not imply lack of debris. Since methods for observing marine debris varied between MARAMP surveys in 2003, 2005, and 2007, temporal comparisons are not appropriate. Debris sightings were recorded differently—with sightings in 2003 recorded as a direct part of diver observational methods and sightings in 2005 and 2007 recorded solely as incidental observations by the towed divers in their observer comments. Still, the location of the shipwreck sighting near Bandera Peninsula was the same in 2003 and 2007.

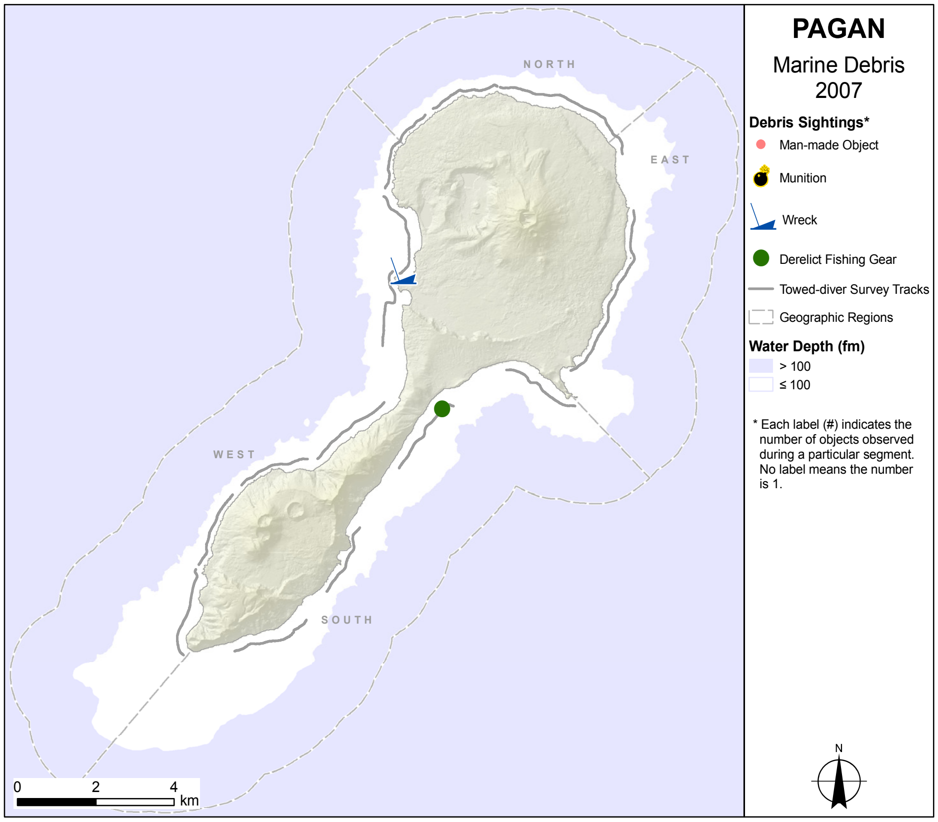


Figure 13.9.1b. Qualitative observations of marine debris from towed-diver benthic surveys of forereef habitats conducted around Pagan during MARAMP 2007. Symbols indicate the presence of specific debris types.

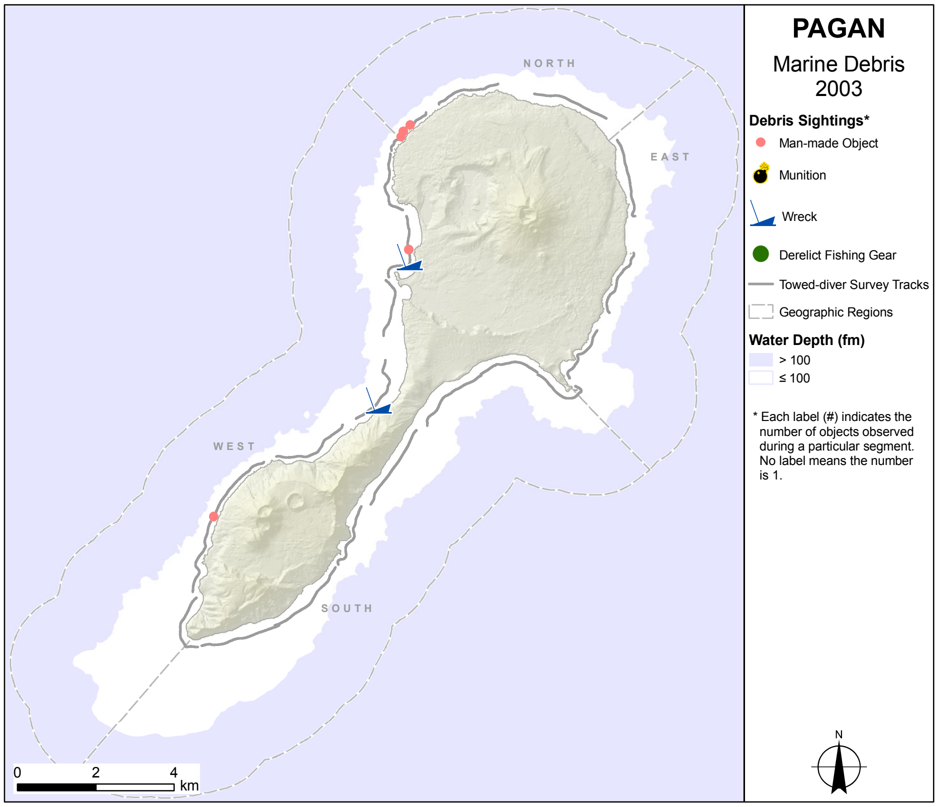


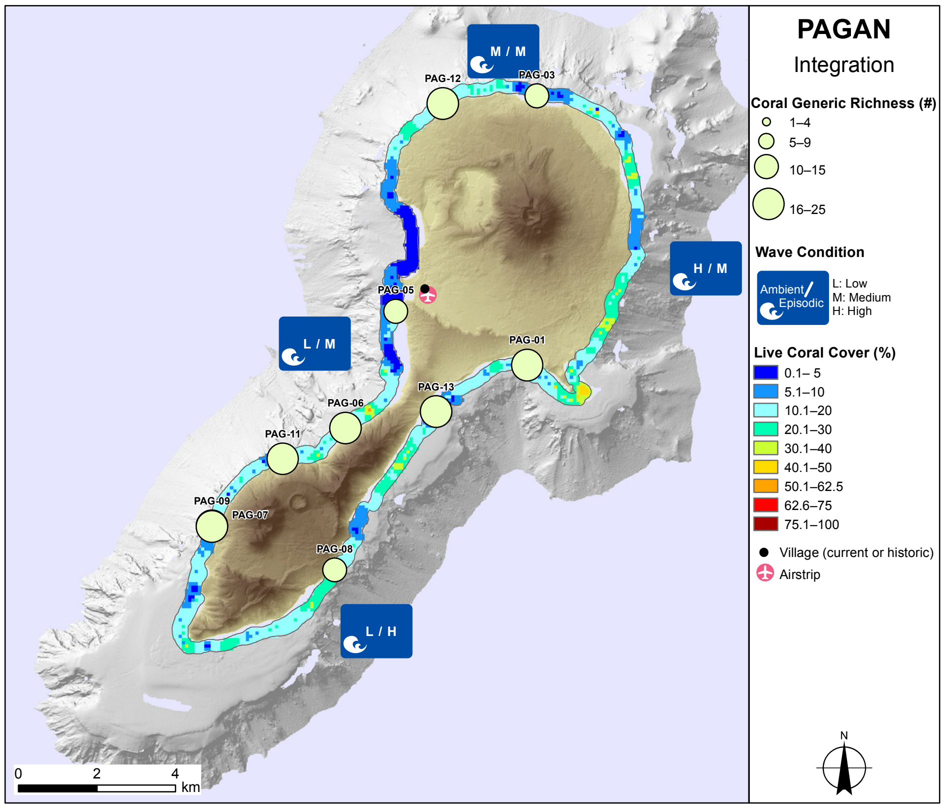
Figure 13.9.1a. Qualitative observations of marine debris from towed-diver benthic surveys of forereef habitats conducted around Pagan during MARAMP 2003. Symbols indicate the presence of specific debris types.

13.10 Ecosystem Integration

The spatial distributions and temporal patterns of individual coral reef ecosystem components around the island of Pagan are discussed in the discipline-specific sections of this chapter. In this section, key ecological and environmental aspects are considered concurrently to identify potential relationships between various ecosystem components. In addition to this island-level analysis, evaluations on an archipelagic scale of different ecosystem elements and their potential relationships across the entire Mariana Archipelago are presented in Chapter 3: “Archipelagic Comparisons,” including archipelago-wide reef condition indices with ranks for Pagan as well as the other 13 islands covered in this report.

Pagan is one of the most volcanically active islands in the Mariana Archipelago, and recent volcanic activity undoubtedly has shaped the submarine habitats surrounding this island. The seascape around Pagan reflects the onshore topography, which is dominated by Mount Pagan in the north and a smaller volcano in the south (for place-names and their locations, see Figure 13.2a in Section 13.2: “Survey Effort”).

Figure 13.10a. Observations of live-hard-coral cover (%) from towed-diver surveys and generic richness from REA surveys conducted on forereef habitats around Pagan during MARAMP 2003, 2005, and 2007. Values of coral cover represent interpolated values from the 3 MARAMP survey years, and generic-richness values represent averages of data from the 3 survey years. A large, blue icon indicates the level of ambient and episodic wave exposure for each geographic region.



The geology of northern Pagan is characterized by lava flows and deposits from different eruptive events. The largest known eruption occurred in 1981, but ongoing volcanic activity has included eruptions in 2006 and 2010 and gas discharges in subsequent years. In the north, bathymetry reveals the flanks of Mount Pagan steeply sloping to depths > 2000 m (see Figure 13.3.1a in Section 13.3.1: “Acoustic Mapping”). Numerous ridges and pinnacles also are present on these slopes. Towed-diver surveys reported spur-and-groove habitat and continuous reef with cover of live hard corals within a range of 0%–30% (Fig. 13.10a). South of Mount Pagan, the reef area around the tip of the Sengao Peninsula near Togari Rock supported the highest coral cover in 2003, within a range of 40.1%–62.5% over 8 segments (see Figure 13.5.1a in Section 13.5.1: “Coral Surveys”). During MARAMP 2005 and 2007, in this area stressed-coral cover > 10% was observed (Figs. 13.5.1c and e) and COTS were fairly common (Fig. 13.10b; see also Figures 13.7.1f and g in Section 13.7: “Benthic Macroinvertebrates”). No clear difference in total fish biomass between the southeastern coast and other areas at Pagan was observed from REA surveys for fishes of all species and sizes (see Figures 13.8.1e, f, and g in Section 13.8.1: “Reef Fish Surveys”).

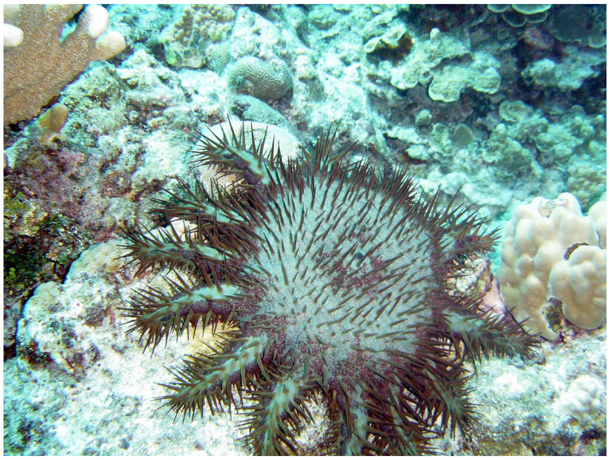


Figure 13.10b. A crown-of-thorns seastar (*Acanthaster planci*) preying on corals at Pagan. *NOAA photo by Robert Schroeder*

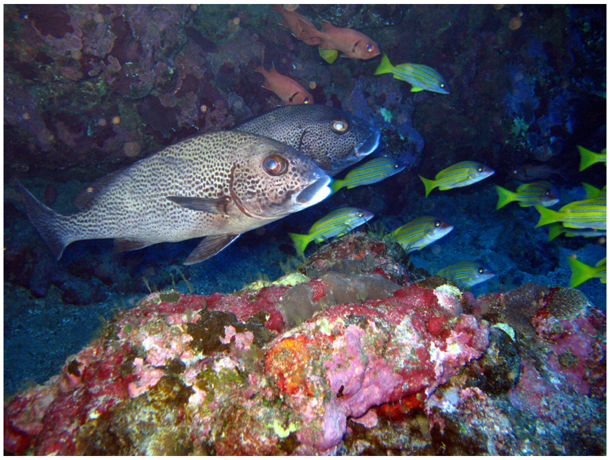


Figure 13.10c. Reef fishes, (*left to right*) the painted sweetlip (*Plectorhinchus picus*), blotcheye soldierfish (*Myripristis* berndti), and common bluestripe snapper (*Lutjanus kasmira*), observed during a survey conducted at Pagan. *NOAA photo by Danny Merritt*

One area west of Mount Pagan was distinctive with a habitat characterized as low complexity and soft sediment that supported very little live coral cover or macroalgal cover (see Figures 13.3.3a and c in Section 13.3.3: "Habitat Characterization" and Figure 13.6.1a in Section 13.6.1: "Algal Surveys"). This area, inside a bay north of Bandera Peninsula, is located just downslope from 2 lakes formed in craters west of Mount Pagan, and, thus, onshore topography provides a possible conduit for transport of sediments there.

Large-fish biomass in the north region and the northern part of the west region, assessed using towed-diver surveys, was fairly similar overall to the biomass values observed in other regions around Pagan. The highest biomass of large fishes found during the 3 MARAMP survey years was from a single survey conducted in 2003 in the northern part of the west region (see Figure 13.8.1a in Section 13.8.1: "Reef Fish Surveys"). Data from REA fish surveys suggested high levels of total fish biomass in the north region, compared to other areas surveyed at Pagan. The highest mean biomass in 2003 was seen at REA site PAG-03 near Tarage in the north region, and the highest mean biomass in 2007 was observed at PAG-12, also in the north region (Fig. 13.10c and Figs. 13.8.1e and g).

A narrow isthmus separates Mount Pagan in northern part of Pagan from the smaller volcano in the southern part. On either side of this isthmus, towed-diver surveys found moderately complex, hard substrate habitat that supported moderate amounts of live coral cover relative to other areas surveyed around Pagan (see Figures 13.3.3a and c in Section 13.3.3: "Habitat Characterization"). The levels of coral-colony density recorded during REA benthic surveys on either side of this isthmus (at sites PAG-06 and PAG-13) also were moderate during the 3 MARAMP survey years, compared to other sites surveyed at this island (see Figures 13.5.1b, d, and f in Section: 13.5.1: "Coral Surveys"). East of this isthmus, a shallow shelf forms one of the two anchorage areas at Pagan (see Figure 13.3.1b in Section 13.3.1: "Acoustic Mapping"); the other is located west of this isthmus. Relatively high live coral cover, within a range of 50.1%–62.5%, was recorded during a single segment of the towed-diver survey conducted along the narrowest portion west of Pagan's isthmus in both 2005 and 2007 (Figs. 13.5.1c and e). This high cover value was attributed to a large field of *Euphyllia ancora* and *Porites rus* observed during the survey. Surrounding areas did not support the same level of live coral cover but instead exhibited the low coral cover typically found around much of Pagan, relative to the rest of the Mariana Archipelago.

The bathymetry around southern Pagan is similar to the bathymetry around the northern part of this island, with steep slopes descending to depths > 3000 m as well as ridges and pinnacles (see Figure 13.3.1a in Section 13.3.1: "Acoustic Mapping"). A large, shallow shelf in the south region extends southwest ~ 3 km from South Point (Fig. 13.3.1c). Mound-like features on this shallow shelf suggest the presence of coral reef habitats; however, the optical-validation data collected on this shelf are insufficient for verifying this possibility. TOAD surveys conducted east of this shelf at depths of 30–40 m suggested low coral cover of 20% in some areas, but these surveys were not extensive (Fig. 13.3.3c). Some of the highest levels of coral-colony density recorded during the 3 MARAMP survey years were seen at PAG-07 and PAG-09, in the southern part of the west region, with 45–56 colonies m^{-2} (see Figures 13.5.1b, d, and f in Section: 13.5.1: "Coral Surveys"). Values of coral cover observed during both REA and towed-diver surveys in this area were low relative to averages recorded around Pagan. Total fish biomass from REA surveys off the southern coasts of Pagan was similar to the total fish biomass values found in other survey areas at Pagan.

Overall, values of coral cover recorded around Pagan were low to moderate in comparison to levels seen at other islands in the Mariana Archipelago. No clear spatial patterns were observed for live coral cover around Pagan across the 3 survey years, other than the near absence of corals in the bay north of Bandera Peninsula. Hydrographic surveys conducted in 2005 and 2007 revealed temperature, salinity and density values that were lower in the east and south regions of Pagan than in the west and north regions. Such a strong east–west pattern was not reflected in surveys of benthic communities around Pagan. Patches of high coral cover were observed relatively infrequently and often not recorded in the same place during different survey years, probably as a result of differences in survey locations and depth between years. Effects of COTS predation may have masked other natural factors in the observed variability in coral distribution around Pagan. COTS were observed in high abundance, compared survey results from the rest of the Mariana Archipelago, in many areas around Pagan in both 2005 and 2007.

13.11 Summary

MARAMP integrated ecosystem observations provide a broad range of information: bathymetry and geomorphology, oceanography and water quality, and biological observations of corals, algae, fishes, and benthic macroinvertebrates along the forereef habitats around Pagan. Methodologies and their limitations are discussed in detail in Chapter 2: "Methods and Operational Background," and specific limitations of the data or analyses presented in this Pagan chapter are included in the appropriate discipline sections. Methods information and technique constraints should be considered when evaluating the usefulness and validity of the data and analyses in this chapter. The conditions of the fish and benthic communities and the overall ecosystem around Pagan, relative to all the other islands in the Mariana Archipelago, are discussed in Chapter 3: "Archipelagic Comparisons."

This section presents an overview of the status of coral reef ecosystems around the island of Pagan as well as some of the key natural processes and anthropogenic activities influencing these ecosystems (for place-names and their locations, see Figure 13.2a in Section 13.2: "Survey Effort"):

- Pagan was formed by 2 large volcanoes, which are separated by a narrow isthmus. With a land area of 47 km^2, it is the fourth largest island of the CNMI.

- Human habitation on Pagan has been sporadic and mainly seasonal since the evacuation of this island's residents in 1981 after the largest documented volcanic eruption of Mount Pagan occurred.

- The seascape around Pagan reflects the onshore topography, which is dominated by Mount Pagan in the north and a second, smaller volcano in the south. Bathymetry reveals the steeply sloping flanks of Mount Pagan descending to depths > 2000 m. Numerous ridges and pinnacles also are present on these slopes. Bathymetry is similar in southern Pagan, with steep slopes descending to depths > 3000 m.

- Habitats in the north and east regions were characterized, during towed-diver surveys conducted at depths of ~ 14 m, as fairly complex with hard substrate. Limited optical data from TOAD surveys, conducted at depths of 50–100 m, suggested mainly hard substrates with patchy sand cover. Analyses of video footage from these TOAD surveys show very little live coral cover, with live corals observed only in isolated video frames.

- In the northern parts of the south and west regions, low-complexity and soft-sediment habitats supported very little live coral cover. On either side of this island's narrow isthmus, habitats were moderately complex and characterized as hard substrate with moderate amounts of live corals. Around South Point, sand cover was more common and habitat complexity lower than in other areas around Pagan. South of Pagan, analyses of TOAD video footage obtained at depths of 15–100 m suggest only few live corals, with estimates of 20% coral cover for some video frames at depths up to ~75 m.

- Wave model output shows that ambient trade wind swells impacted the east and, to a lesser extent, the north. Episodic wave energy from storm tracks impacted the south and, to a lesser extent, the west, north, and east.

- In situ SST data from a buoy deployed off Bandera Peninsula show that water temperatures there rose above the coral bleaching threshold in August 2005. Given the relatively short duration and small magnitude of this period of elevated temperature, widespread mass coral bleaching was unlikely.

- Islandwide mean coral cover from towed-diver surveys during the 3 MARAMP survey years ranged from 10% to 19%. Estimates of live coral cover from the 9 REA sites surveyed at Pagan in 2007, using the line-point-intercept method, ranged from 3.9% to 20.6% with an overall sample mean of 10.6%. The highest coral cover was seen on either side of this island's isthmus at PAG-13 (20.6%) and PAG-06 (16%).

- Coral disease surveys, conducted using the belt-transect method at 9 REA sites around Pagan in 2007, detected 28 cases of coral disease. Overall mean prevalence of coral disease was 0.02%. Fungal infections, accounting for 90% of disease cases recorded at Pagan, and other syndromes of unknown etiology, contributing 10% of cases found, were identified at only 3 of the sites surveyed. More than 95% of the afflictions involving fungal infections were observed on corals of the genus *Cyphastrea*.

- Overall mean macroalgal cover for Pagan, based on towed-diver surveys, was essentially the same in 2005 (18%) and 2007 (17%). The greatest variability between these survey years occurred in the survey area west of Tarage in the north region with a 43% decrease in macroalgal cover. Also, macroalgal cover near Hira Rock in the east region decreased from 32% to 9% between these survey years. In the south region, near Piarama, a large increase in macroalgal cover from 7% to 39% was observed between the same survey periods.

- Between MARAMP 2003 and 2007, islandwide mean crustose-coralline-red-algal cover increased 7%, based on towed-diver surveys. Coralline-algal disease was found in 2007 at only one REA site, PAG-01 east of Degusa in the south region. Two cases of a single affliction, coralline lethal orange disease, were enumerated at this site.

- The overall mean biomass of large fishes from towed-diver surveys was highest in 2003 with 0.87 kg 100 m^{-2}; biomass values were 0.37 kg 100 m^{-2} in 2005 and 0.41 kg 100 m^{-2} in 2007. The lower levels observed in 2005 and 2007 reflect a decline in sightings of sharks and snappers in those years.

- From REA surveys of fishes of all sizes and species, the overall mean total fish biomass for Pagan across the 3 survey periods, at 8.90 kg 100 m^{-2}, was a little lower than the average observed for the unpopulated islands but more than 3 times the biomass values found around Guam and Saipan.

- Giant clams were observed at low levels of abundance around Pagan during the 3 MARAMP survey periods. Sea cucumbers were uniformly distributed around Pagan at moderate daytime densities, relative to survey results from other islands of Mariana Archipelago.

- Based on towed-diver surveys, COTS were virtually non-existent in 2003. During MARAMP 2005, observed COTS densities were much higher than levels recorded in 2003. In several localized areas in all regions around Pagan, COTS densities were high enough to suggest that they may have been experiencing a COTS outbreak. By 2007, population densities had decreased; however, localized areas in the west, south, and east regions had densities suggesting possible outbreaks.

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